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ALLEVIATION OF AERODYNAMICALLY INDUCED VIBRATION IN THE SERGEANT MISSILE

H. CARL THORMAN

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REPORT No. 20-124

ALLEVIATION OF AERODYNAMICALLY INDUCED VIBRATION IN THE SERGEANT MISSILE

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JET PROPULSION LABORATORY
California Institute of Technology
Pasadena, California
January 30, 1959

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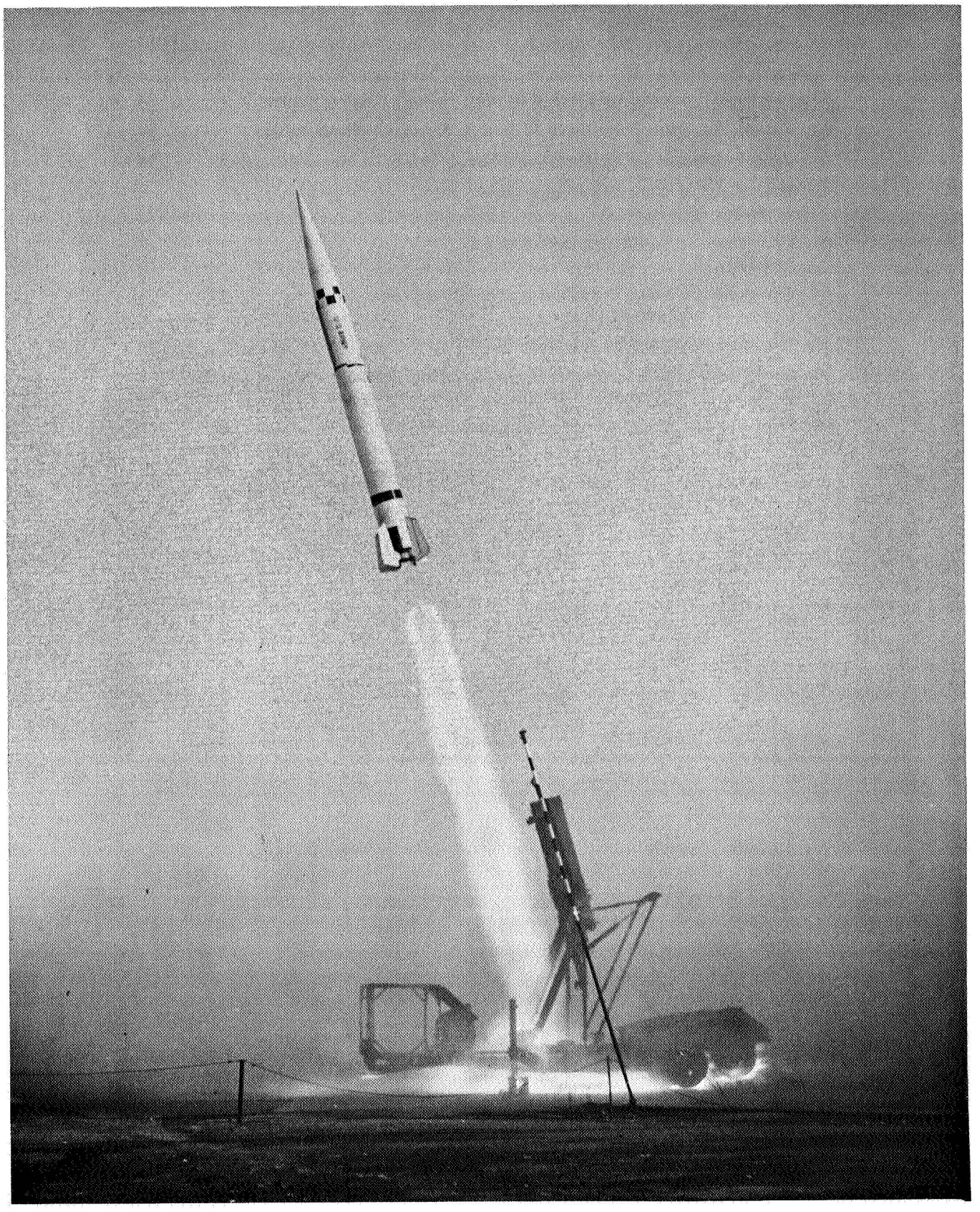


ABSTRACT

Vibrations generated by aerodynamic noise associated with the *Sergeant* dragbrake were alleviated by modification of the dragbrake-blade planform. The wind-tunnel and flight tests, and the resulting development of the modified blade, are described. It was found that a cutout near the blade root significantly decreased aerodynamic noise without reducing drag appreciably.

I. INTRODUCTION

The vibration environment due to the high level of aerodynamic noise generated by the original *Sergeant* dragbrake blades (Block I and Block II designs) constituted a serious threat to the reliability of the missile guidance system. From a series of wind-tunnel tests of various dragbrake-blade planforms it was determined that, by providing a cutout of appropriate size through the blade near its root, the aerodynamic noise level could be significantly reduced without appreciably reducing the drag produced by the dragbrake.

Blade planforms of this type were introduced into the firing program in August 1958. Data from five flight tests of these modified blades indicate that the vibration environment has been satisfactorily alleviated and is no longer a threat to *Sergeant* reliability. Furthermore, the drag increment produced by the modified blades is adequate to provide the correction capability necessary to meet the range requirements which are specified in the official Military Characteristics for the *Sergeant* weapons system.

II. DESCRIPTION OF DRAGBRAKE

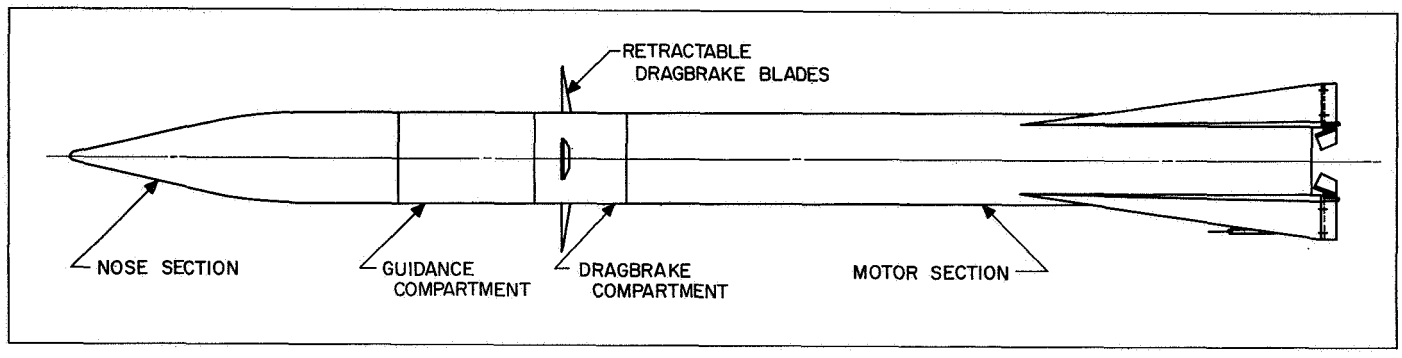


Fig. 1. *Sergeant* Block I Airframe

The range, or distance, of the ballistic trajectory of the *Sergeant* solid-propellant surface-to-surface guided missile is controlled primarily by an aerodynamic dragbrake which operates three times during the course of flight. The first braking period provides gross adjustment of range; the two remaining braking periods provide correction for nonstandard performance and atmospheric conditions.

The dragbrake consists of four flat-faced blades and an actuating mechanism to extend the blades into the airstream. The missile drag with blades extended is approximately five times as great as the drag with blades retracted. The brake is actuated in a plane normal to the missile axis. The actuation time for extending or retracting the blades is 1.25 sec.

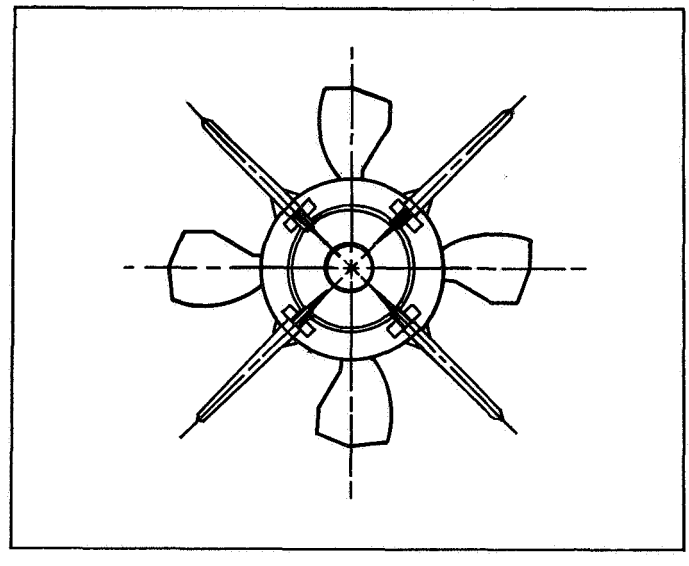


Fig. 2. Block I Dragbrake Configuration, Rear View

A. Block I Configuration

Figure 1 shows the Block I missile configuration, which was used for the eight rounds fired during Phase I of the *Sergeant* flight test program. The purpose of this phase of the program was to prove the integrity of the airframe and propulsion system and to demonstrate the feasibility of the *Sergeant* weapon system.

In the Block I configuration, the faces of the four dragbrake blades were located in a single plane. The blade planform shown in Fig. 2 represents the maximum blade area which could be accommodated in this manner.

Values of the drag-increment coefficient ΔC_D produced by the Block I dragbrake are shown in Fig. 3, as estimated from full-scale flight test results and as measured in wind-tunnel tests on a 1/16-scale model.

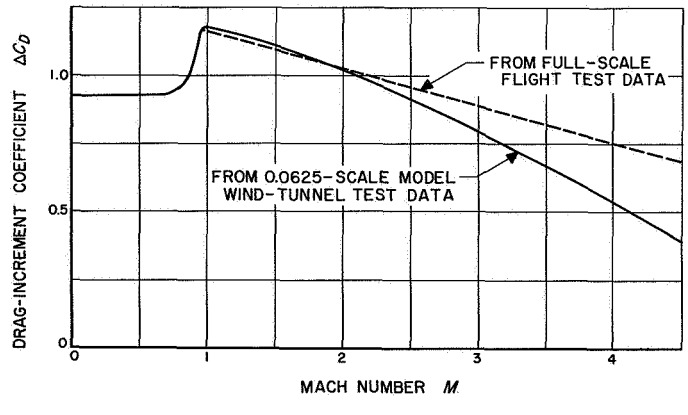


Fig. 3. Dragbrake Drag Increment with Block I Blade Planform

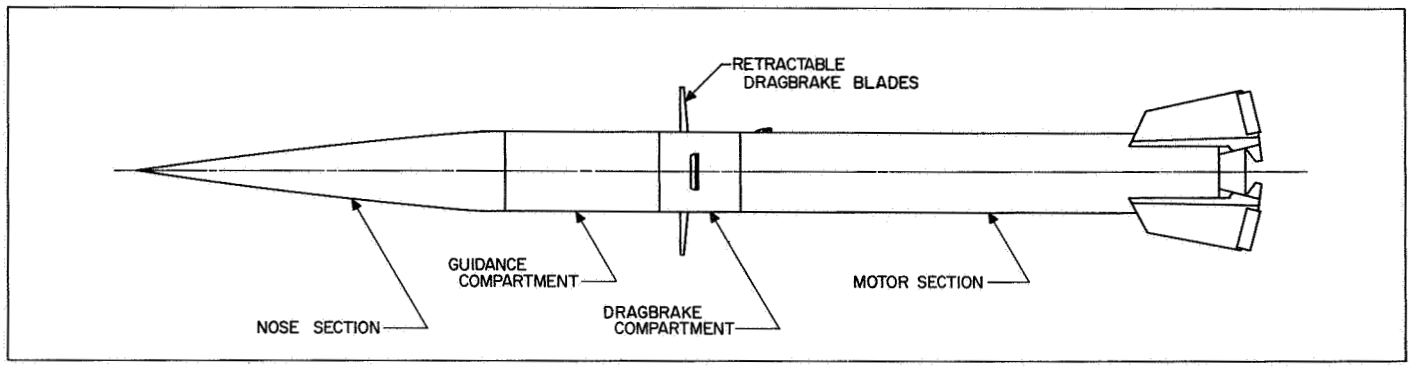


Fig. 4. *Sergeant* Block II Airframe

B. Block II Configuration

Figure 4 shows the Block II missile configuration, which was introduced into the flight-test program beginning with Firing 9. For the Block II configuration, a "staggered" dragbrake-blade arrangement was adopted, in which one pair of blades is located slightly aft of the other pair, to provide a blade envelope 25% larger than the Block I blade envelope. In general, the geometry of the Block II airframe represents the intended aerodynamic configuration of the final, tactical *Sergeant* missile.

The Block II dragbrake-blade planform used on Firings 9, 11 and 13[1] is shown in Fig. 5. Wind-tunnel and flight-test measurements of the drag-increment coefficient obtained with this blade planform are shown in Fig. 6.

Modified blade planforms, designed to alleviate brake-induced vibration, were tested on Firings 14 to 18. These planforms are compared with the Block II blade planform in Fig. 7. The modified planforms were designed within the envelope of the original Block II planform and therefore required no redesign of the dragbrake compartment. On the basis of the flight-test results, which are described in detail in Section IV of this Report, the 0-33 blade planform[2] shown in Fig. 7c has been tentatively chosen for the final design. In outside dimensions, this planform is identical to the original Block II planform; the cutout at the blade root removes 33% of the original area. No further modification of the dragbrake blade is anticipated at present.

[1]Firing 10 was performed without dragbrake operations. On Firing 12 the missile was inadvertently destroyed prior to the first scheduled dragbrake operation.

[2]Modified blade planforms are designated by two numbers; the first indicates the percentage of Block II blade area removed from the sides, and the second indicates the percentage removed by root cutout.

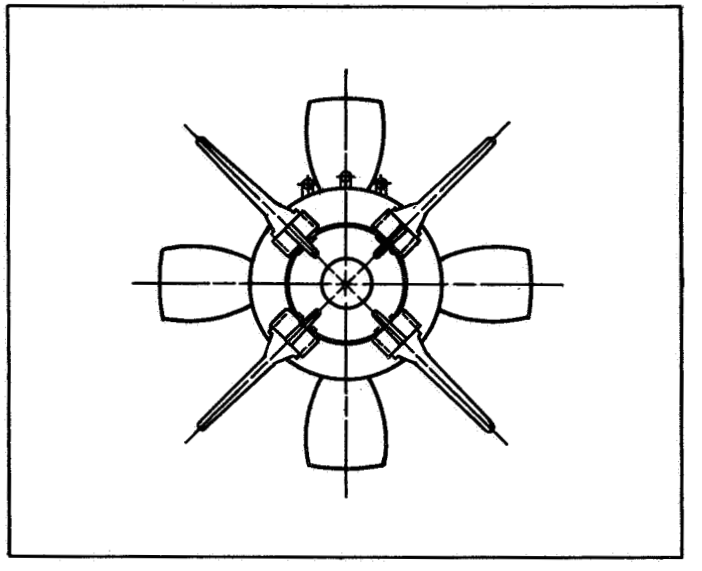


Fig. 5. Block II Dragbrake Configuration, Rear View

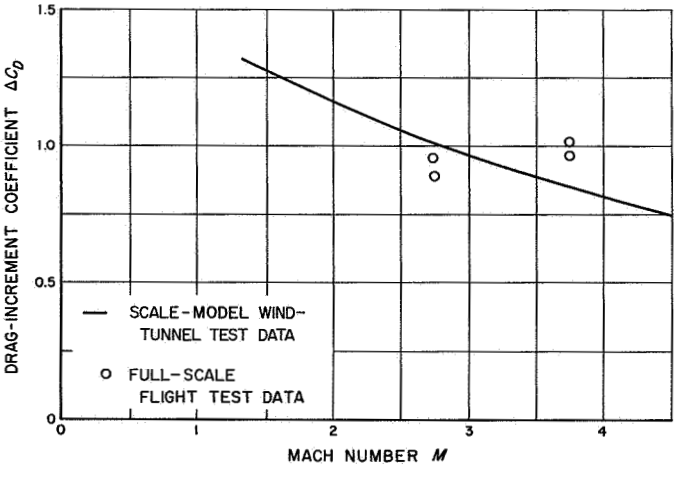


Fig. 6. Dragbrake Drag Increment with Block II Blade Planform

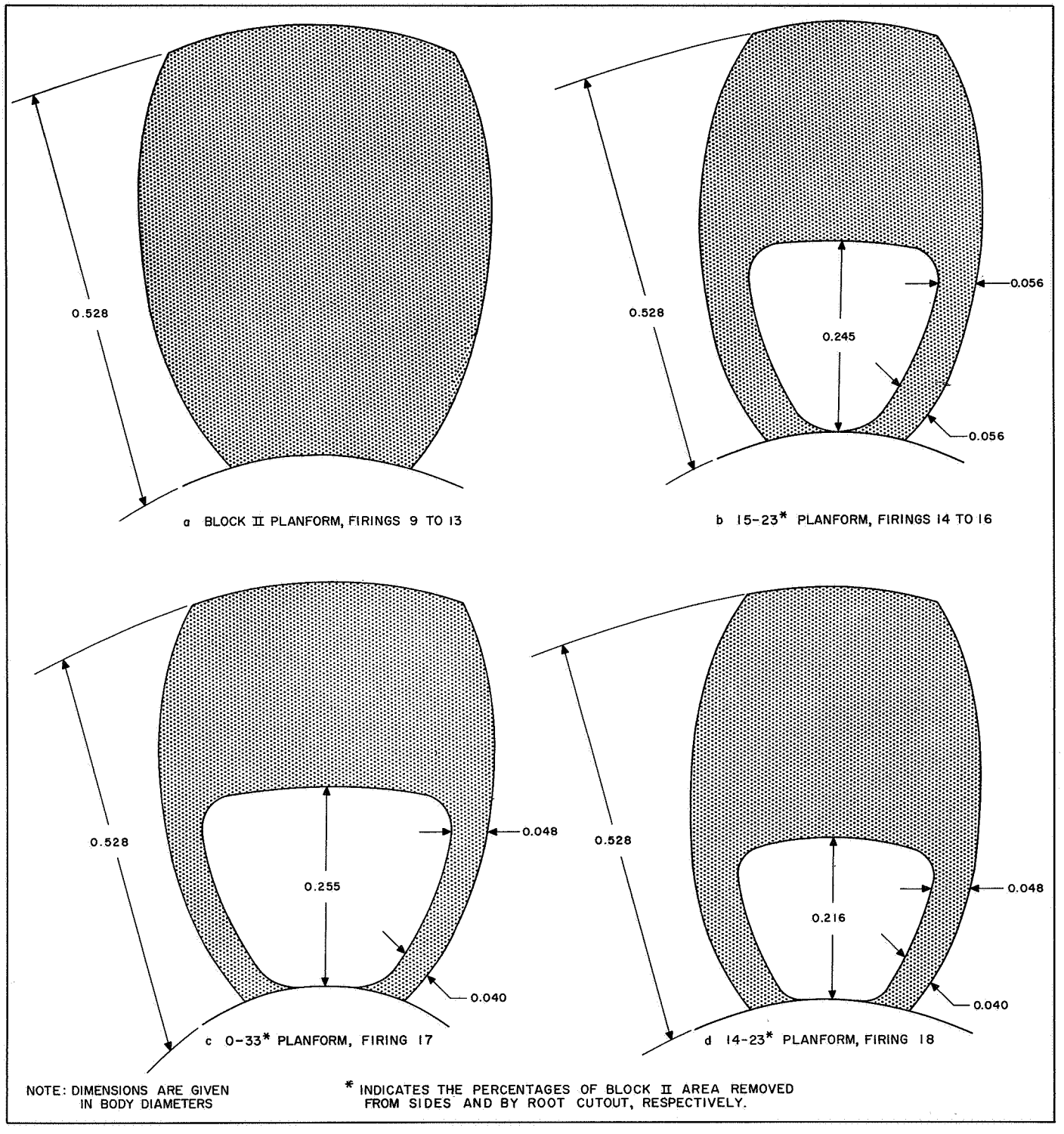


Fig. 7. Dragbrake-Blade Planforms Tested in Phase II Firings

Results of Firing 17 indicate that, in the Mach-number range from 1.1 to 2.4, the average value of drag-increment coefficient with the 0-33 blade planform was about 1.0, a value which is comparable to the drag-increment coefficient obtained with the original Block II blade planform (Fig. 6).

III. AERODYNAMIC-NOISE AND VIBRATION RESEARCH

Vibration measurements obtained from *Corporal* Firing 1410 (October 1954) and early *Sergeant* Block I Firings (1956) demonstrated that the dragbrake could produce a prohibitively severe vibration environment in the guidance compartment. Consequently, a program of exploration into aerodynamic-noise and vibration phenomena was undertaken with the object of developing methods to reduce the dragbrake-induced vibration environment in the *Sergeant* missile. Areas of investigation covered in the program were as follows:

1. Continuation of vibration measurements in flight, with particular emphasis on the determination of vibration levels actually experienced by the guidance system equipment.
2. Wind-tunnel and flight tests to investigate the aerodynamic sources of vibration associated with various dragbrake-blade designs.
3. Studies of methods of revising the *Sergeant* standard trajectories to reduce peak drag loads.
4. Examination of the vibration transmission of the *Sergeant* structure.

Results of items 1 to 3 and their application to the reduction of the vibration environment are summarized in the present Report.

Since the vibration input was satisfactorily reduced by modifying the dragbrake blade and revising the braking schedule along the flight trajectory, it was unnecessary to change the vibration transmission of the missile structure. Consequently, the results of the analyses and tests which were conducted under item 4 are not reported here.

A. In-Flight Vibration Measurements

The character of the in-flight vibration environment measured by accelerometers at various locations in the Block I missile may be described as follows:

1. The predominant vibration levels in the guidance compartment occurred during the braking portions of the flight.
2. The vibration levels were found to be directly related to drag level.
3. The observed acceleration spectra were essentially flat in the 20-to-2000-cps frequency range studied. (The frequency response of the flight telemetering equipment restricted the measurements to frequencies below 2000 cps.)
4. The measured amplitude distribution corresponded very closely to a Gaussian distribution curve, indicating a random amplitude distribution.

The flat, Gaussian nature of the measured accelerations permits representation of the severity of vibrations by means of the root-mean-square (rms) level for a specified bandwidth. In Fig. 8 the rms level (20-to-2000-cps band) of vibration in the axial direction at the aft end of the guidance compartment on one of the longerons (which support the dragbrake blades) is shown as a function of drag during braking. Accelerometer measurements at that location are presumed to represent the vibration input to the guidance compartment.

As shown in Fig. 8, the vibration levels measured in flight at the location mentioned were as high as 40 *g* rms.

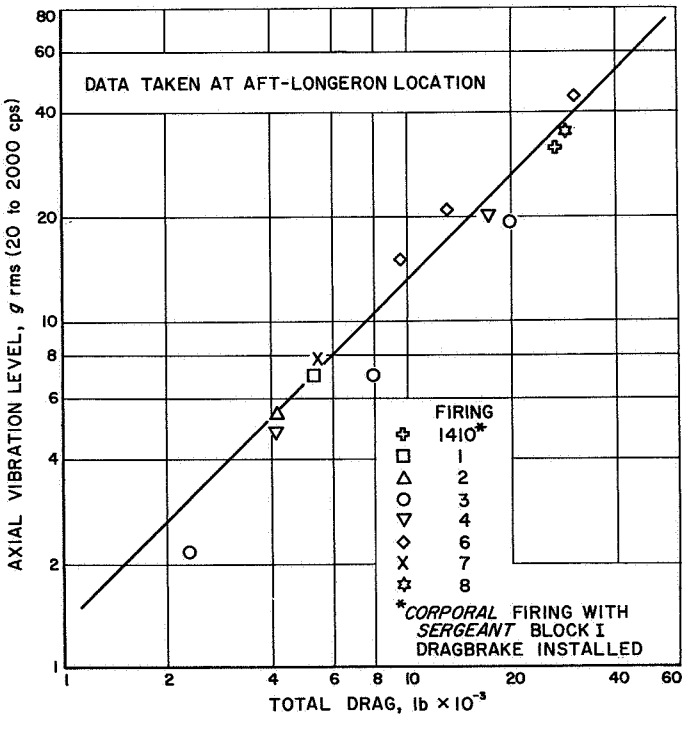


Fig. 8. Vibration Measurements Obtained in Flight with Block I Dragbrake Blades Extended

Furthermore, from the relationship established by these data it could be predicted that under certain extreme conditions the Block I dragbrake would produce vibration levels of over 60 *g* rms.

B. Wind-Tunnel Tests

The character of the vibration environment observed in flight suggested that the vibrations were due primarily to random air-flow disturbances (aerodynamic noise) in the neighborhood of the dragbrake, rather than resonant oscillations of the dragbrake blades.

1. Preliminary investigation. Studies of aerodynamic noise produced by the dragbrake were incorporated into the initial scale-model tests of the aerodynamic characteristics of the Block II *Sergeant* missile (SWT 20-226 and 20-242), conducted in the JPL 20-inch Supersonic Wind Tunnel in 1956 and early 1957.

The flow pattern produced by the dragbrake was observed by means of spark shadowgraphs such as that shown in Fig. 9. The flow pattern illustrated in Fig. 9 is established as follows: extension of the dragbrake blade into the supersonic air stream produces a strong, normal shock wave which strikes the turbulent boundary layer[3] on the body and causes boundary-layer separation. The resulting separated flow region produces an oblique shock wave similar to that produced by a solid conical surface. At the intersection of the oblique and normal shock waves a vortex sheet or "slipstream" is formed, due to the velocity difference between the fluid which has passed through two shocks and the fluid which has passed through only one shock.

The steady-state pressure distribution on the Block II dragbrake blade, at a Mach number of 3.0, is shown in Figs. 10 and 11. These measurements were obtained on a ⅛-scale model with four blades installed. From these data it is apparent that the portion of the blade blanketed by the separated flow produces very little drag.

The aerodynamic sources of vibration may be classified as follows, according to the three flow regions shown in Fig. 12.

1. Pressure fluctuations in the separated-flow region forward of the blade.
2. Pressure fluctuations in the region between the normal shock and the front face of the blade.
3. Velocity fluctuations caused by shedding vortices in the wake region behind the blade.

Investigations of aerodynamic noise associated with the *Sergeant* dragbrakes have been concerned primarily with regions (1) and (2).

Fastax motion pictures, taken through a schlieren optical system, indicated that the oblique shock wave was not stationary but tended to fluctuate rapidly. Thus, in addition to the fluctuations inherent in the separated flow, disturbances could be fed into the unseparated flow by

[3]To simulate the full-scale flight condition, a turbulent boundary layer was obtained by the use of a suitable amount of grit on the nose of the model.

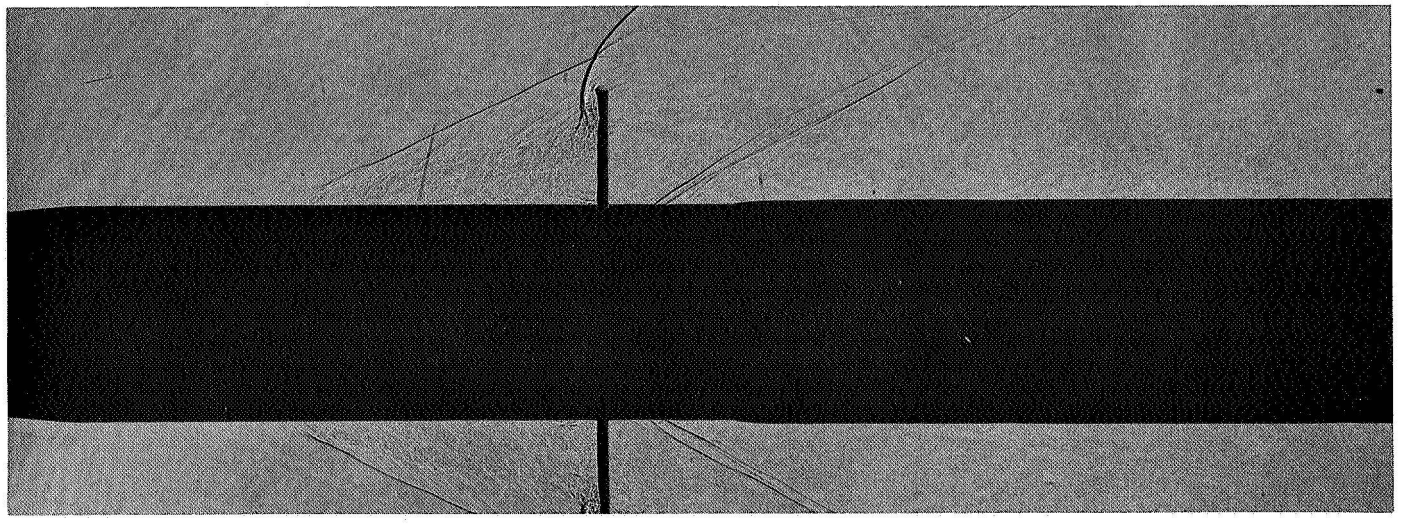


Fig. 9. Spark Shadowgraph Showing Typical Flow Pattern Produced by Dragbrake Blades

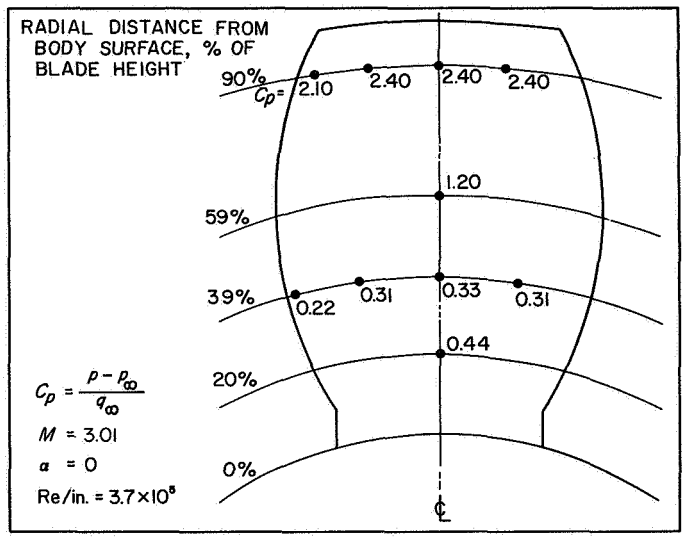


Fig. 10. Steady-State Pressure-Coefficient Distribution on Front Face of Block II Blade

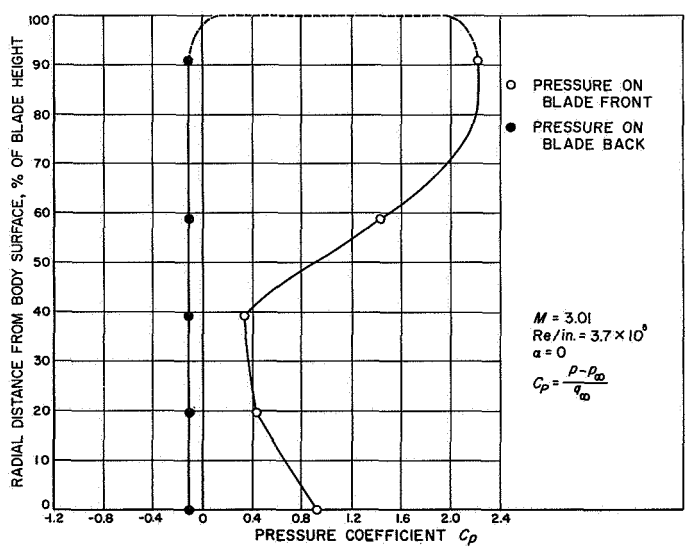


Fig. 11. Steady-State Pressure-Coefficient Distribution along Radial Centerline of Block II Blade

the oscillation of the oblique shock wave. Attempts to stabilize the oblique shock wave, by providing a fixed protuberance on the model slightly ahead of the separated-flow region, were unsuccessful.

An Altec-Lansing condenser-type microphone was installed in the 1/16-scale Block II *Sergeant* model (Fig. 13) to measure the sound-pressure level on the body surface in the separated-flow region ahead of the dragbrake. The microphone measurements verified that the pressure fluctuations in that region were extremely high in comparison to the fluctuations at the same location with the dragbrake retracted. A typical plot of the sound-pressure spectra obtained in these tests is shown in Fig. 14.

2. 1957 scale-model tests. Since the only important difference between the Block I and Block II blade planforms was the blade size, it could be expected that the Block II blades would produce at least as severe a vibration environment as the Block I blades did. In order to develop a dragbrake which would produce significantly less vibration without appreciably reducing the available drag increment, many planform modifications were investigated on a 1/8-scale model of the *Sergeant* forebody (Fig. 15) in the JPL 20-inch Supersonic Wind Tunnel.

In the three tests (SWT 20-260, 20-270, and 20-276) conducted during 1957, planform modifications within the basic envelope of the Block II planform were compared at $M = 3.0$ and $Re/\text{in.} = 3.7 \times 10^5$. As shown in Fig. 16, the instrumentation of the model included provisions for condenser-microphone measurements of the sound-pressure levels on the body and on the blade to evaluate the vibration-producing potential of each planform.

In test SWT 20-260, the following comparison was obtained between two classes of planforms (Fig. 17) having 15% less area than the Block II planform:

Class 1, planforms derived by removing area from the blade tip: This removal of area from the high-drag region reduced the drag increment by a greater percentage than that of area removed. There was no reduction in the size of the separated-flow region (see Fig. 18) nor any reduction in sound-pressure level in that region.

Class 2, planforms derived by removing area near the blade root: This type of modification *increased* the

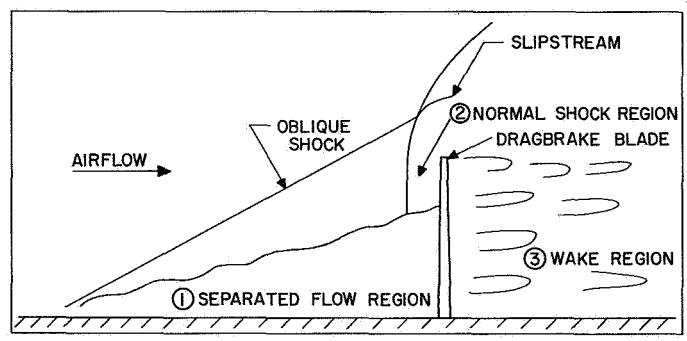


Fig. 12. Diagram Showing Classification of Aerodynamic Sources of Vibration

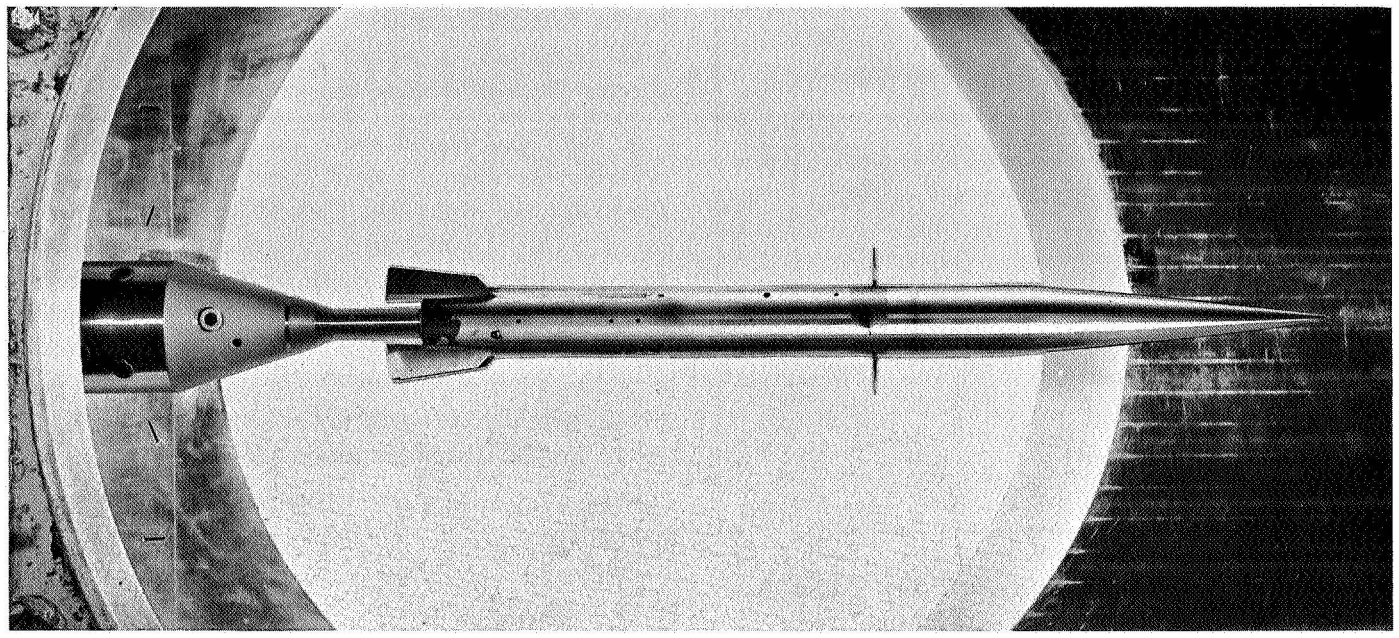


Fig. 13. *Sergeant* 1/16-Scale Model Installed in JPL 20-Inch Supersonic Wind Tunnel

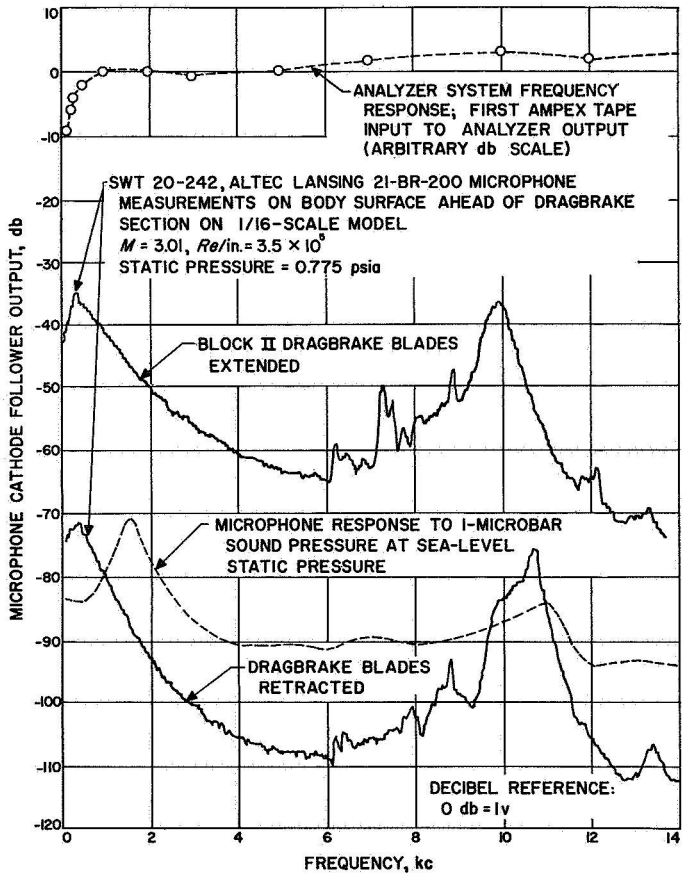


Fig. 14. Sound-Pressure Spectra on Body Surface with and without Dragbrake Blades Installed

drag increment by 6%. This increase was apparently due to a decrease in the extent of the separated-flow region (Fig. 18). Although this modification decreased the area affected by the pressure fluctuations in the separated-flow region, there appeared to be no appreciable reduction in the intensity of fluctuations at the point of measurement (location M1, Fig. 16).

Further variations in planform were included in tests SWT 20-270 and SWT 20-276. Data from these two tests are summarized in Figs. 19 and 20, where the

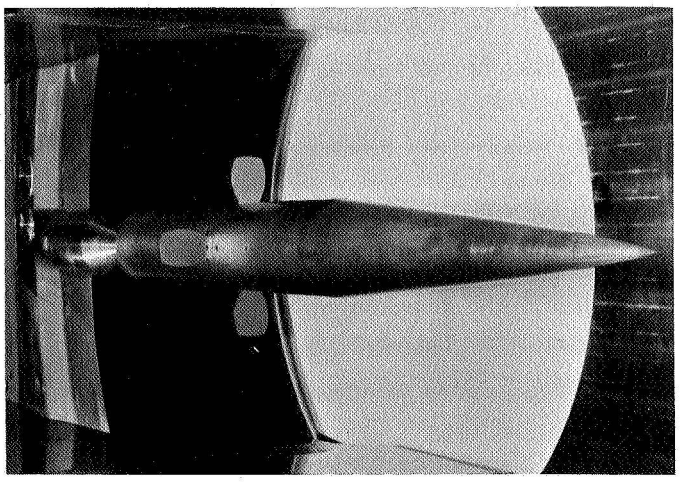


Fig. 15. *Sergeant* 1/8-Scale Forebody Model Installed in JPL 20-Inch Supersonic Wind Tunnel

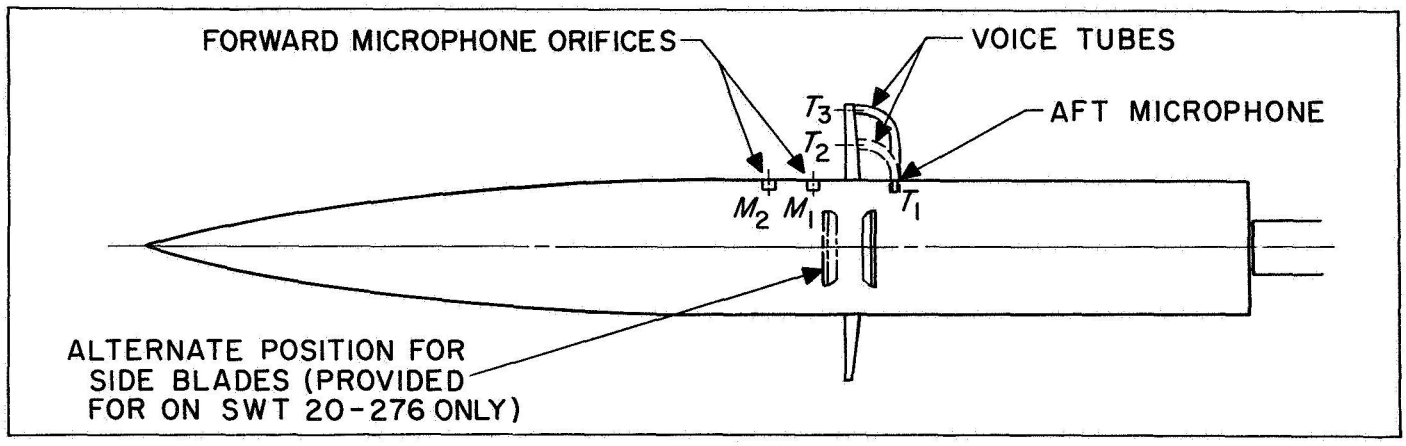


Fig. 16. Microphone Instrumentation on 1/8-Scale Forebody Model for Tests SWT 20-260, 20-270, and 20-276

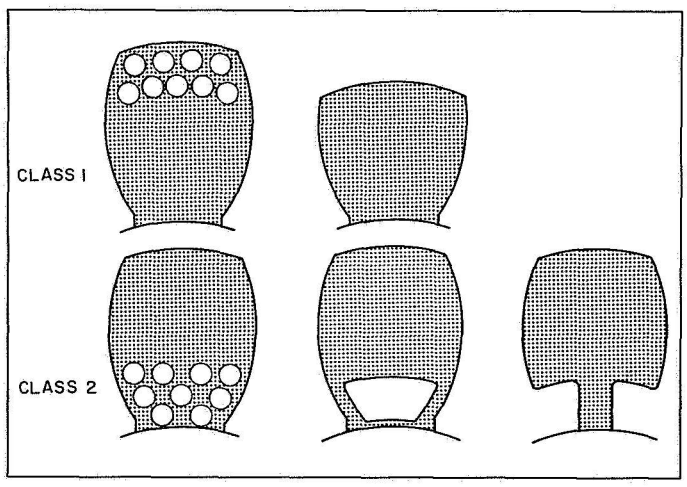
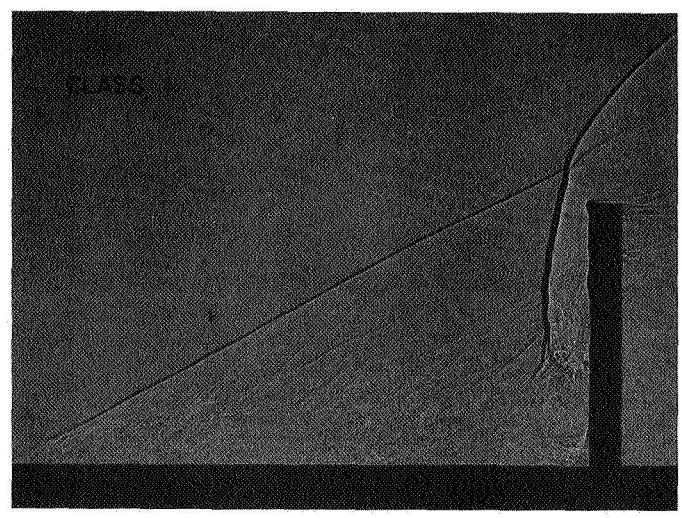


Fig. 17. Two Classes of Blade Planforms Tested in SWT 20-260



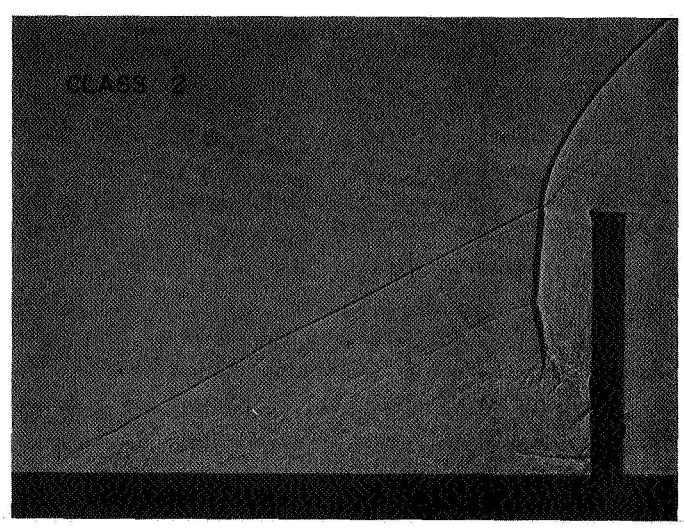


Fig. 18. Comparison of Flow Patterns on Class 1 and Class 2 Planforms at Mach 3.0, SWT 20-260

aerodynamic-noise and drag-increment characteristics of each planform are presented relative to the corresponding characteristics of the Block II planform.

The results of test SWT 20-270 suggested that substantial reduction of sound-pressure levels both at the blade tip and on the body surface could be provided by a planform having area removed from the sides of the blade (A, Fig. 19) or a planform having area removed from the sides and from the root (B, Fig. 19). A planform having circular holes distributed over the entire blade (G, Fig. 19) afforded nearly the same reductions of sound pressure, but offered no capability for further modification.

Planforms incorporating the features of planforms A and B of Fig. 19, but using a double-strut design, were

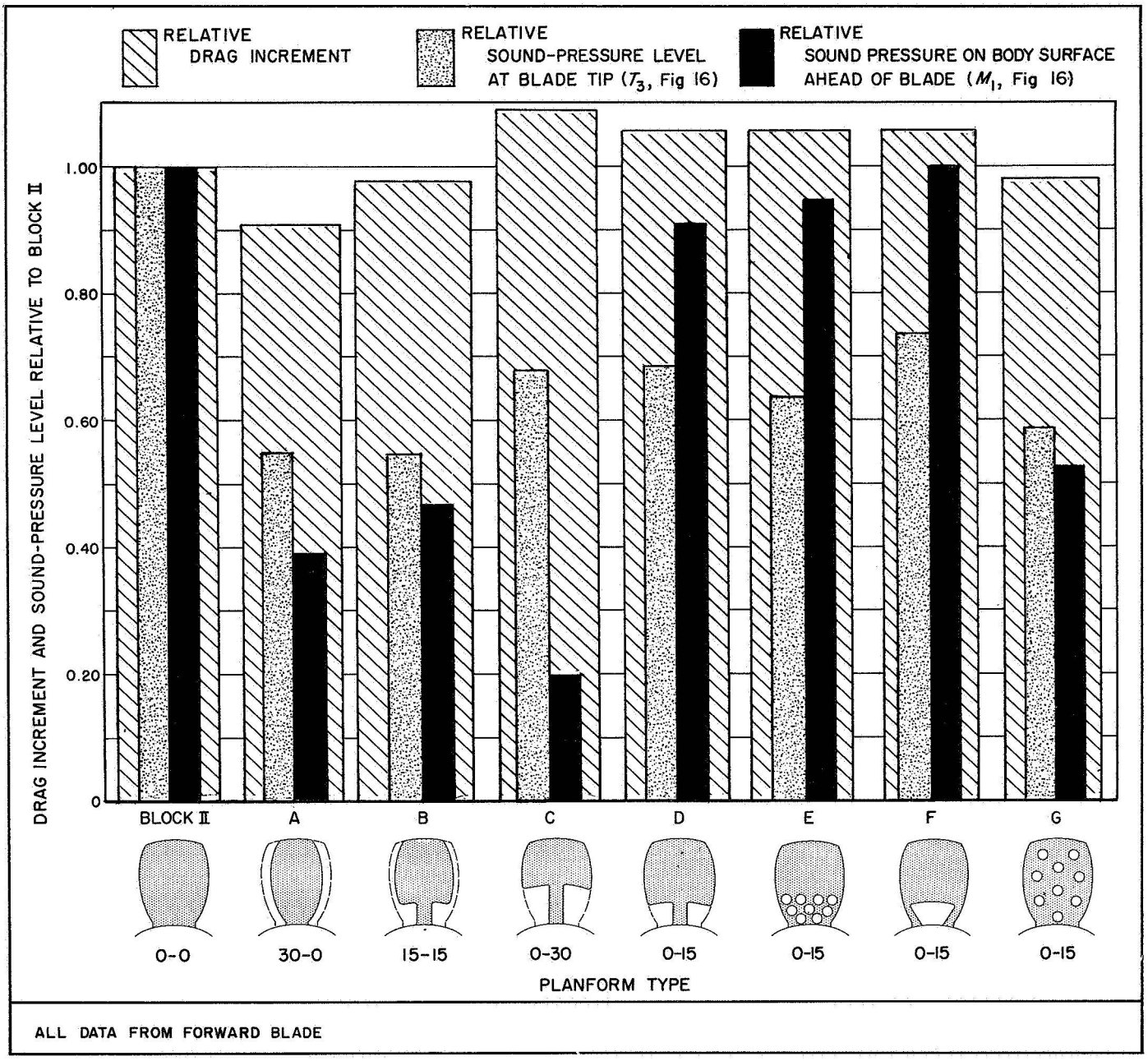


Fig. 19. Comparison of Sound-Pressure Levels and Drag Increments for Various Blade Planforms at Mach 3.0, SWT 20-270

further tested in SWT 20-276 (see Fig. 20). Full-scale dragbrake blades similar to B of Fig. 20 were designed for flight testing on Firings 14, 15, and 16.

From Fig. 19 it may be observed that planform C, a full-width planform with 30% of the Block II blade area removed at the root, showed a very significant reduction of sound-pressure level on the body, while providing even more drag increment than the Block II blade. In view of this finding, an experiment to compare the performance of a full-width planform with that of a reduced-width planform, both having the root cutout, was planned for Firings 17 and 18.

As shown in planforms D, E, and F of Fig. 19, the method used for removing a given amount of area at

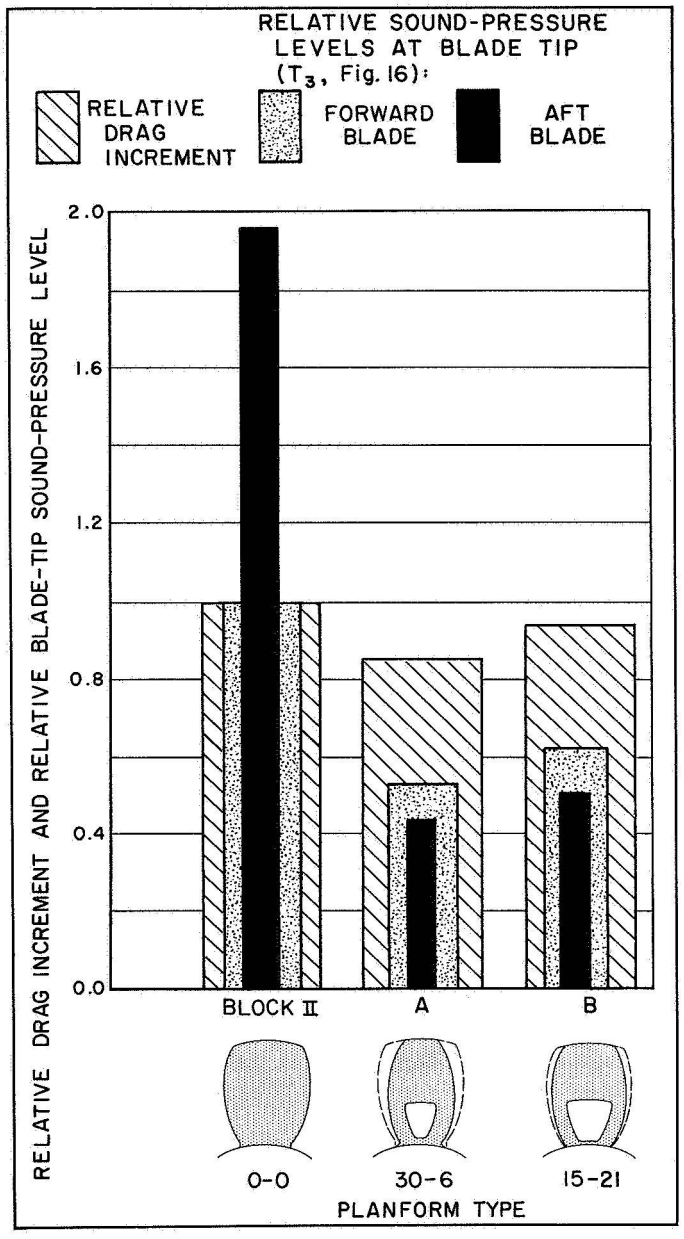


Fig. 20. Comparison of Sound-Pressure Levels and Drag Increments for Various Blade Planforms at Mach 3.0, SWT 20-276

the blade root had very little effect on the aerodynamic results. Consequently, for the flight planform the double strut design was selected to provide torsional rigidity, ease of fabrication, and closure of the airframe when the blades are retracted.

Test SWT 20-276 included measurements on a 1/16-scale complete model (Fig. 13) to determine drag-increment and static-stability characteristics over a range of Mach number. Measurements of drag-increment coefficient with dragbrake blades having the 15-21 type planform (planform B, Fig. 20) and with blades having the Block II planform are compared in Fig. 21. Corresponding static-stability data are presented in Fig. 22.

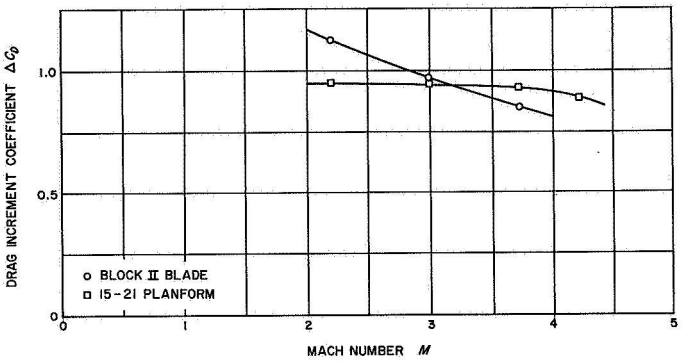


Fig. 21. Comparison of Drag Increments for the Block II and 15-21 Blades as measured on the 1/16-Scale Model, SWT 20-276

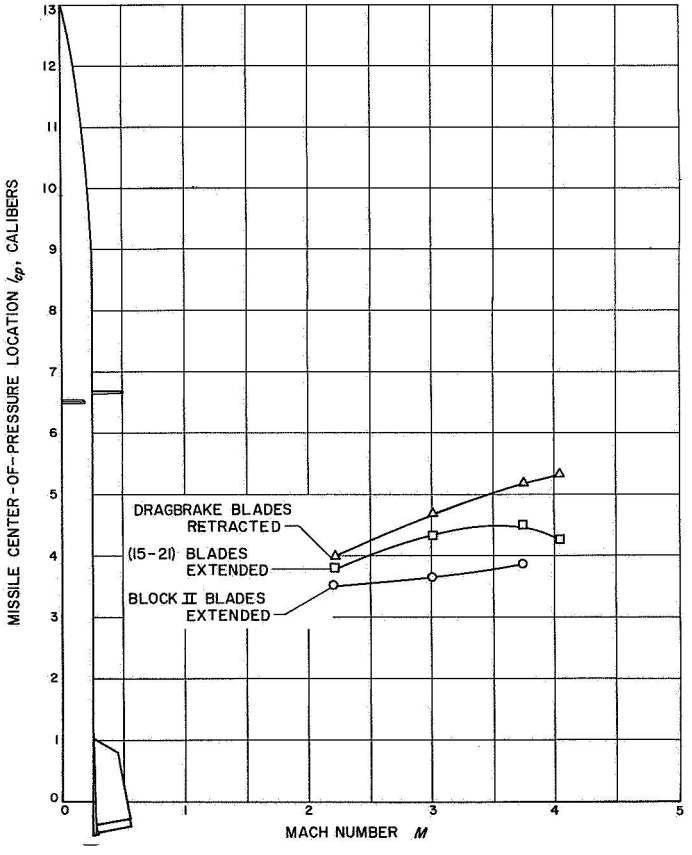
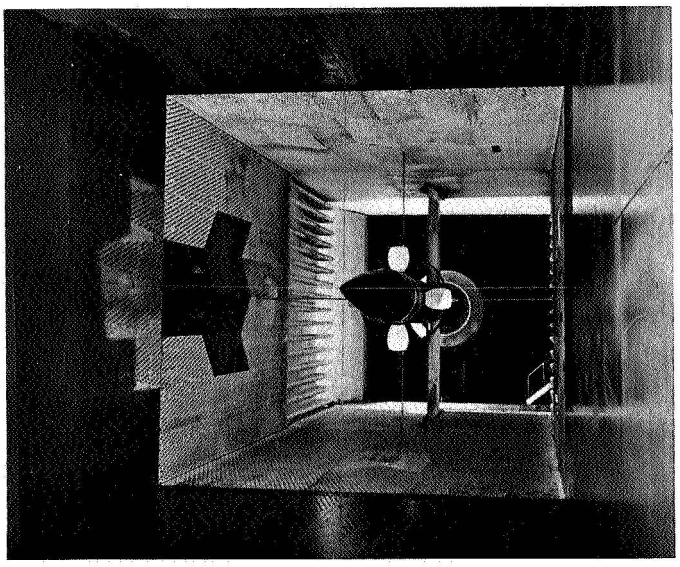


Fig. 22. Effects of Block II and 15-21 Blade Planforms on Missile Center-of-Pressure Location

3. *Full-scale test at AEDC.* In May 1958 the research program was extended to include a test of a full-size *Sergeant* Block II airframe (Fig. 23) in the Transonic Propulsion Wind Tunnel of the Air Force Arnold Engineering Development Center (AEDC) at Tullahoma, Tennessee. The use of a full-scale model afforded structural, as well as aerodynamic, simulation of the missile, thus permitting direct investigation of the vibration environments associated with various dragbrake configurations.



23. Installation of Full-Scale *Sergeant* Airframe in Transonic Wind Tunnel, AEDC

The model was instrumented with accelerometers at several locations in the guidance compartment and on the blades; with static-pressure orifices on the forward and aft blade surfaces and on the guidance compartment skin; and with barium-titanate crystals (to measure sound-pressure levels) on the forward surface of the blades and on the missile skin forward of the blades.

Some important limitations of this test were as follows:

1. No drag measurements were obtained.
2. Mach number was limited to 1.5.
3. Dynamic pressure q was limited to about 5 psi.

In flight the most severe environmental conditions occur in the Mach-number range from 2.4 to 3.0 and at dynamic pressures on the order of 25 psi.

The following three aerodynamic brake configurations were investigated:

1. Block II blade (Fig. 24) to be used as a reference.
2. 15-23 blade (Fig. 25) representing the flight configuration scheduled for Firings 14, 15 and 16.
3. Oversize blade (T-blade[4] with extension, Fig. 26) to exemplify the effects of providing a root cutout large enough to cause the slipstream from the oblique and normal shock intersection, as well as the separated boundary-layer flow, to pass inboard of the blade proper. (Additional blades of this type were studied

[4]The single-strut design of the T-blade was chosen primarily for convenience of modification in testing.

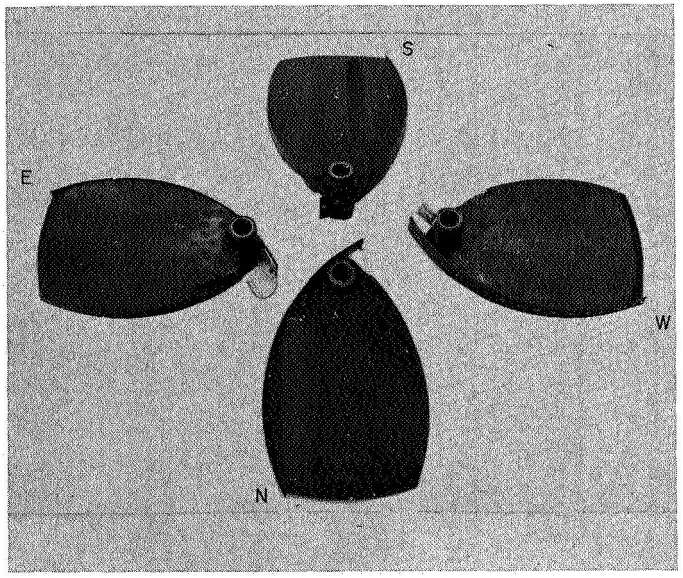


Fig. 24. Block II Blades, AEDC Test

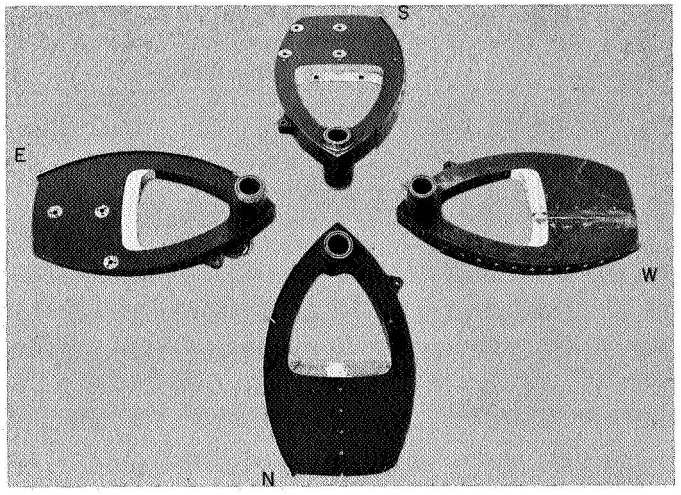


Fig. 25. Blades with 15-23 Planform, AEDC Test

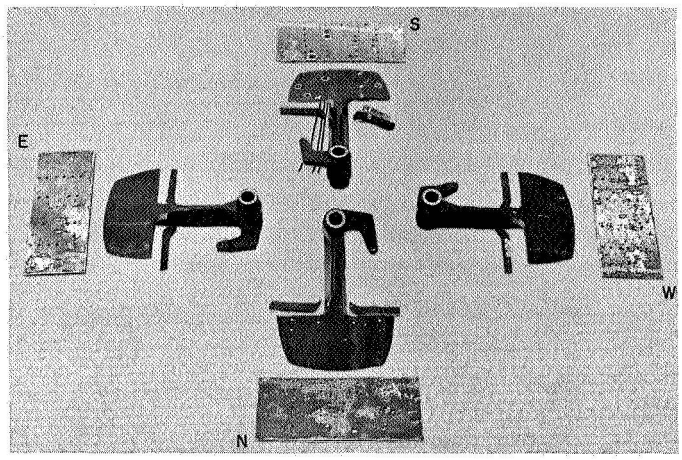


Fig. 26. T-Shaped Blades with Extensions, AEDC Test

in scale-model tests conducted later in 1958 at JPL.) The extensions were installed to provide a drag increment comparable to that of the 15-23 blade. With the extensions, however, the blades could not be retracted into the present brake compartment.

Wideband axial-accelerometer outputs at six locations (Fig. 27) are summarized in Fig. 28. Significant reduction in vibration is apparent as the blade planform was changed from the Block II, to the 15-23 blade, to the T-blade. Finally, the background vibrations of the clean missile (with the blades retracted) are shown. The vibration levels are greatest on the blade and show a general reduction with distance from the blades, except that in the case of the T-blade the vibration on the blade is less than at the first two locations forward of the blade.

Inasmuch as the sting mount supporting the model introduced axial restraint, there was some uncertainty as to whether the vibrational responses observed in the

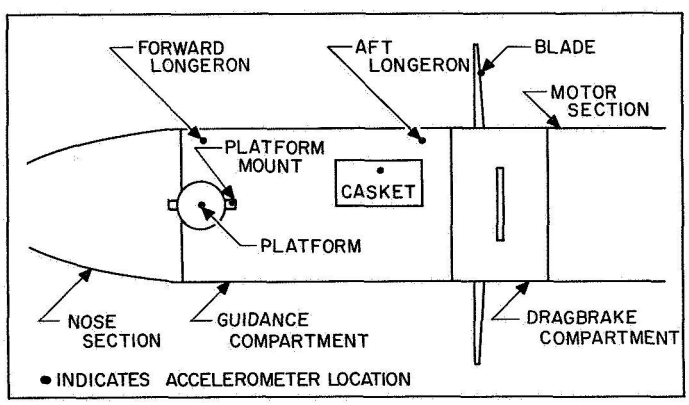


Fig. 27. Accelerometer Locations, AEDC Test

wind-tunnel test were representative of the responses which occur in flight. The distribution of vibration levels (Fig. 28), however, agree in general with distributions obtained in flight tests.

The reductions in vibration levels recorded in Fig. 28 for the 15-23 blade and the T-blade were accompanied by corresponding reductions in the size of the separated-flow region upstream of the blade. Skin static pressure data indicated that (at $M = 1.5$) the flow separation extended upstream of the blades 1.15, 0.80, and 0.65 calibers for the Block II, the 15-23, and the T-blades, respectively.

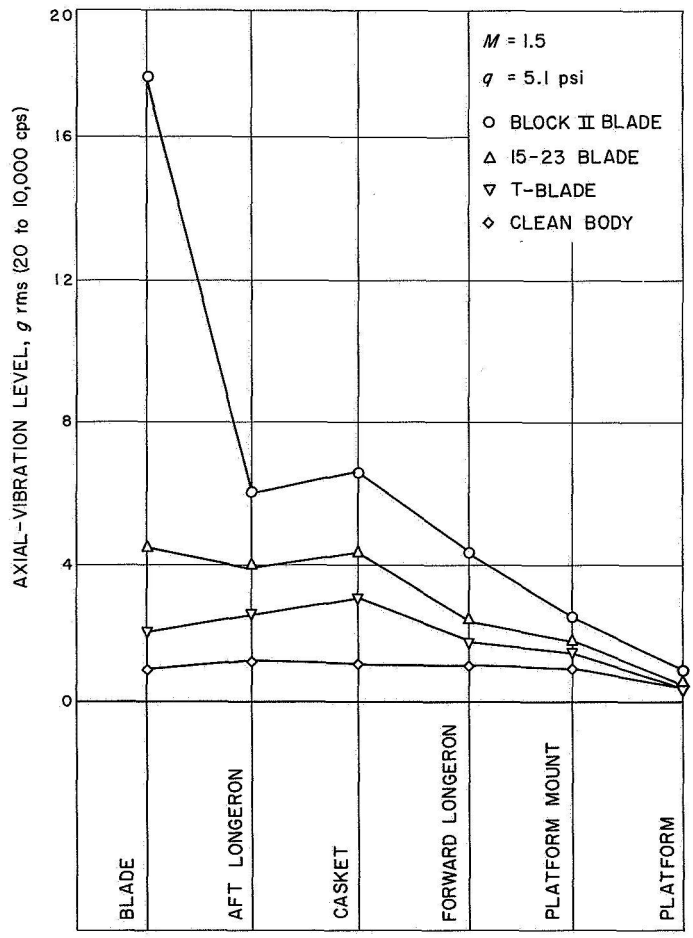


Fig. 28. Axial Accelerometer Readings at Various Locations, AEDC Test

Flight test data had given evidence that the vibration level is a function of gross drag and Mach number. While the AEDC wind tunnel test gave data only at a Mach number of 1.5, the drag could be varied by varying

dynamic pressure. Vibration measurements at the aft-longeron location shown in Fig. 29 tend to confirm the linear dependence of vibration on drag for the Block II and 15-23 blades. From the two data points shown for the T-blade it is, of course, not discernible whether a linear relationship holds for that blade. The drag values shown in Fig. 29 were based on estimated drag coefficients, since no direct measurements of drag were obtained in this test.

In an attempt to determine how much of the vibration is transmitted through the blade and how much is transmitted directly through the skin, an experiment was performed in which Block II dummy blades were supported by an independent structure (Fig. 30) which was in turn

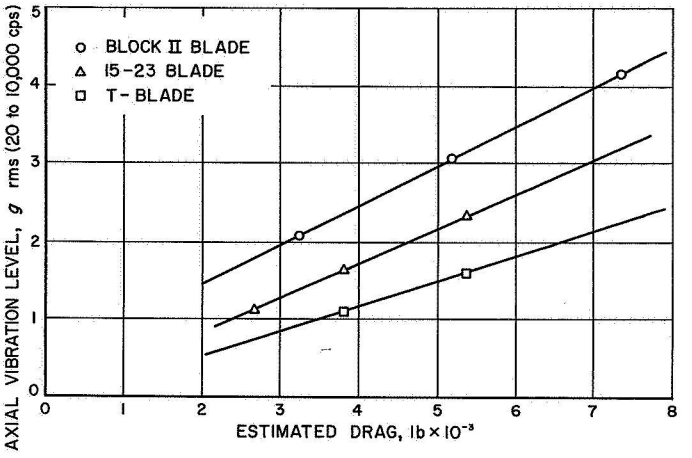


Fig. 29. Vibration at Aft-Longeron Location vs Drag, AEDC Test

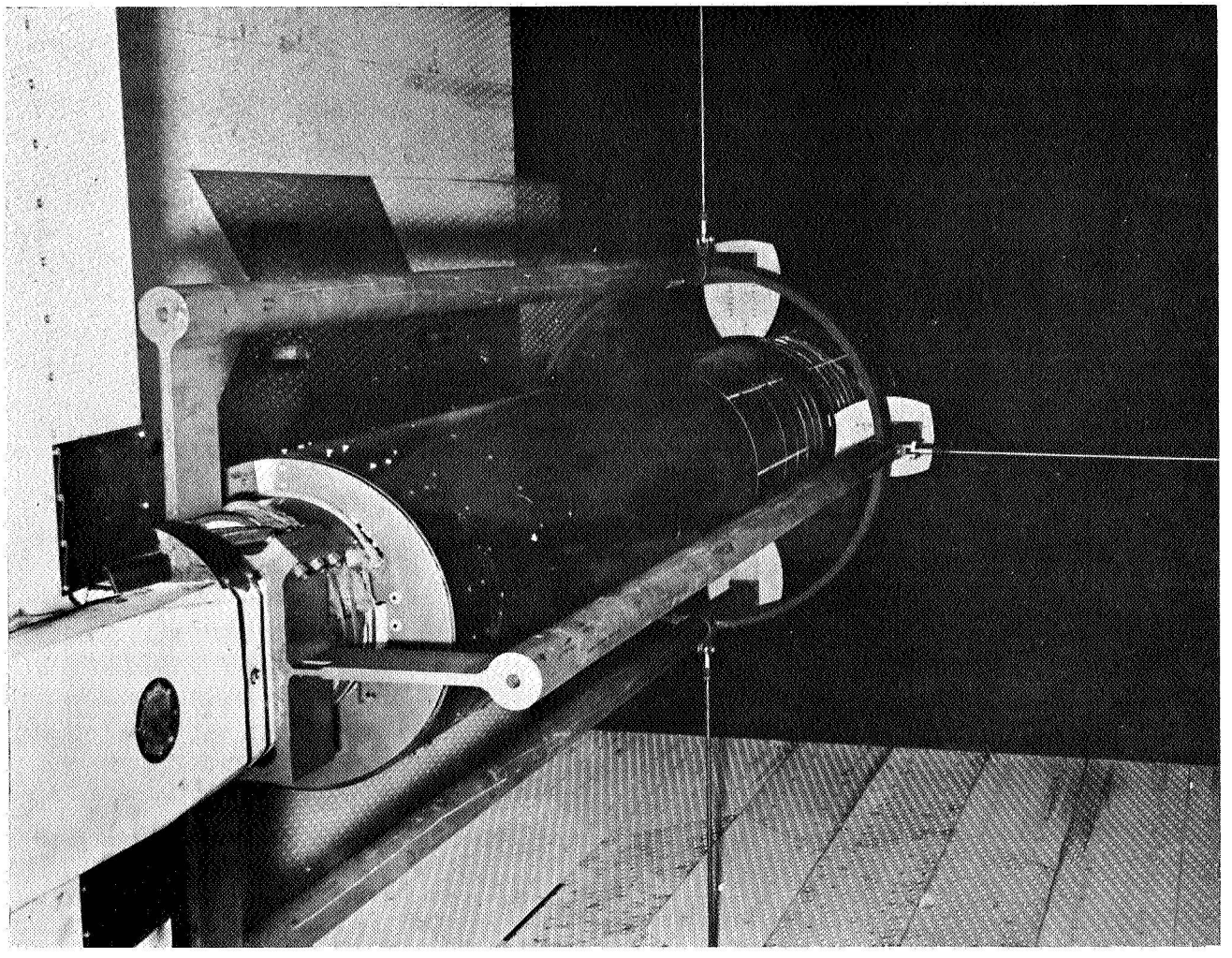


Fig. 30. Rear View of Independent Blade-Support Structure, AEDC Test

mounted on the sting support, rather than on the missile. Figure 31 shows axial-vibration measurements obtained with this configuration compared to measurements obtained with the Block II blades supported by the missile brake compartment. The mechanical detachment of the blades resulted in a vibration reduction of about 20% at the aft-longeron location. If it is assumed that the blade excitation and the missile-skin excitation act as independent sources of vibration and combine in an rms way, and if the independent blade-support can be assumed to have effectively isolated the missile from the blade excitation, it can be concluded that the skin excitation and the blade excitation contributed in the ratio of 3 to 2.

Additional experimentation in the AEDC wind tunnel included the evaluation of a special guidance compartment designed for vibration isolation. In this compartment all guidance packages (or dummies which simulated them) were mounted on a cylindrical shell which was isolated from the central structure of the standard guidance compartment by means of a ⅜-inch sponge-rubber pad. The inertial platform, which is inside of the central tube, was mounted in the standard fashion and consequently had no vibration isolation. For this experiment the Block II blades were used in order to provide a high input level.

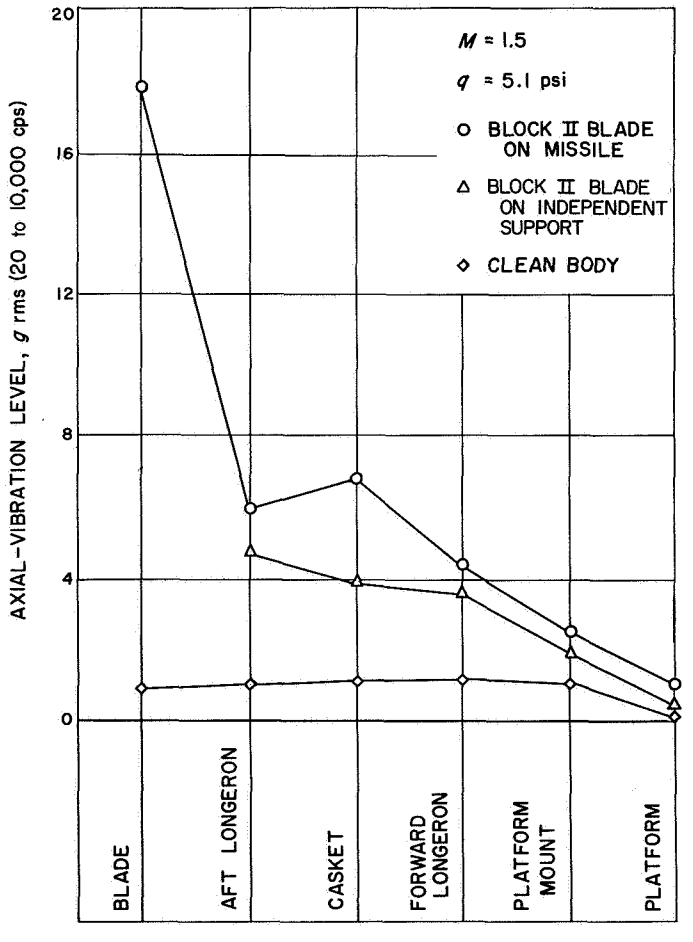


Fig. 31. Comparative Vibration Readings Using Block II Blades Attached to Missile and Supported Independent of Missile, AEDC Test

Direct comparison of rms accelerations observed on the guidance packages with similar observations made on the standard installation under the same aerodynamic conditions indicated that a vibration-level reduction factor of 4 to 6 was achieved. This reduction involved virtually complete elimination of high-frequency vibration and little or no elimination of low-frequency vibration. Complete evaluation of this apparent gain would require further investigation into the following questions:

1. Is this reduction the same at the higher input levels in flight?
2. What are the relative susceptibilities of guidance components to high-frequency and low-frequency vibration?

4. 1958 scale-model tests. A systematic investigation of blade planforms with dimensions scaled from tentative full-scale designs was conducted at various Mach numbers in the JPL 20-inch Supersonic Wind Tunnel in July 1958 (SWT 20-295). A brief additional test was conducted in October 1958 (SWT 20-324) to obtain a final checkout of the two configurations specifically selected for the comparison experiment scheduled for Firings 17 and 18 (see Section IV-B).

The blade planforms investigated in test SWT 20-295 and measurements of their drag-increment characteristics are shown in Figs. 32, 33 and 34, where they are grouped into three families. Within each of the first two families the blade area was varied by changing only the radial dimension of the root cutout. In the third family that dimension was held constant but the overall height and width of the blade were varied.

The full-width planform family (Fig. 32) and the reduced-width planform family (Fig. 33) represent designs which can be accommodated in the present brake compartment with no redesign of the primary structure.

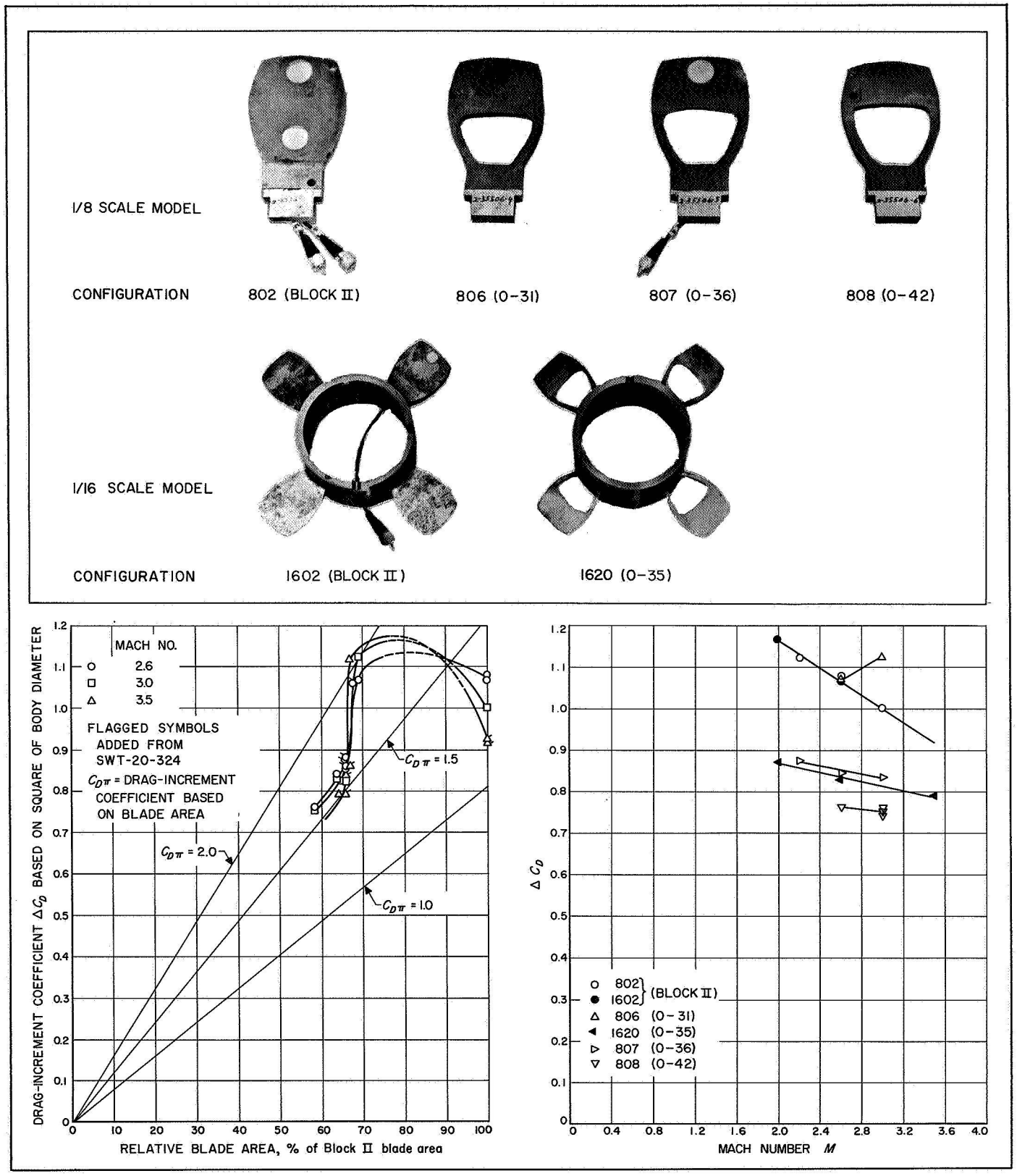
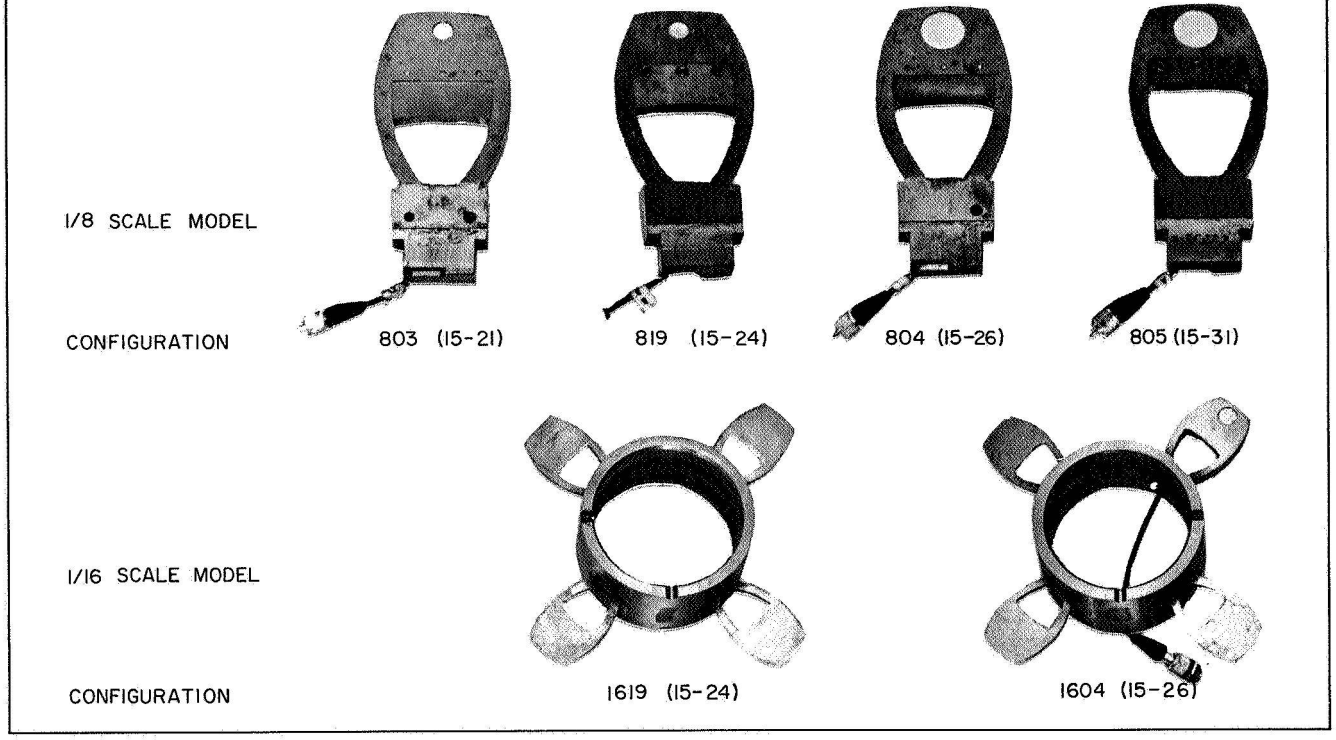
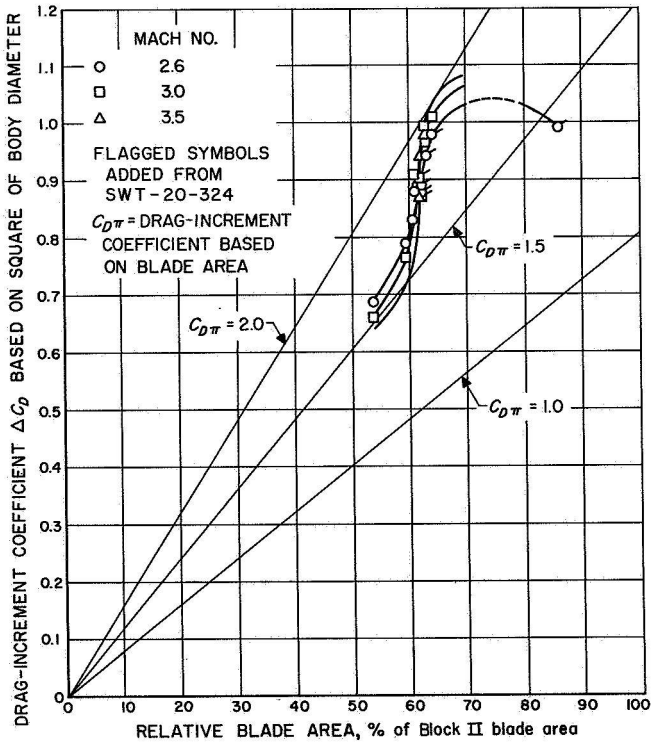


Fig. 32. Blade Configurations and Drag-Increment Characteristics of Full-Width Planform Family, SWT 20-295





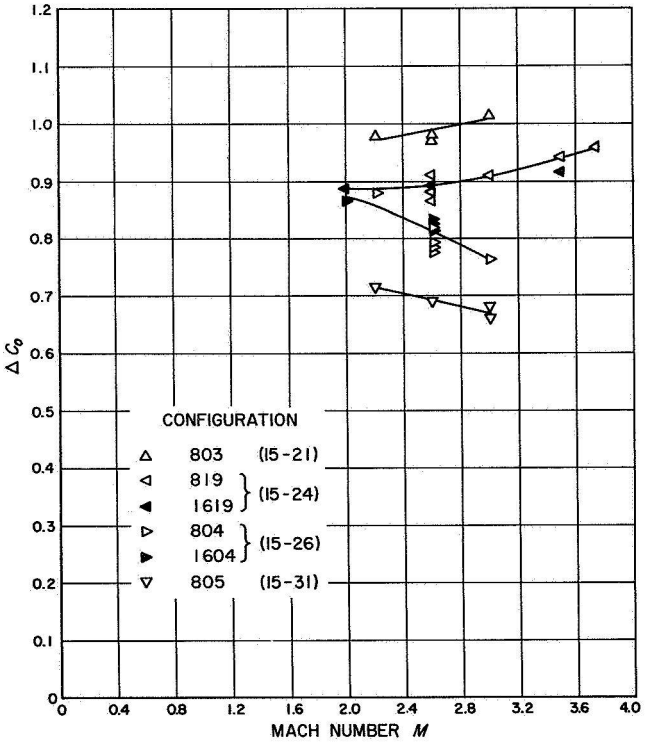


Fig. 33. Blade Configurations and Drag-Increment Characteristics of Reduced-Width Planform Family, SWT 20-295

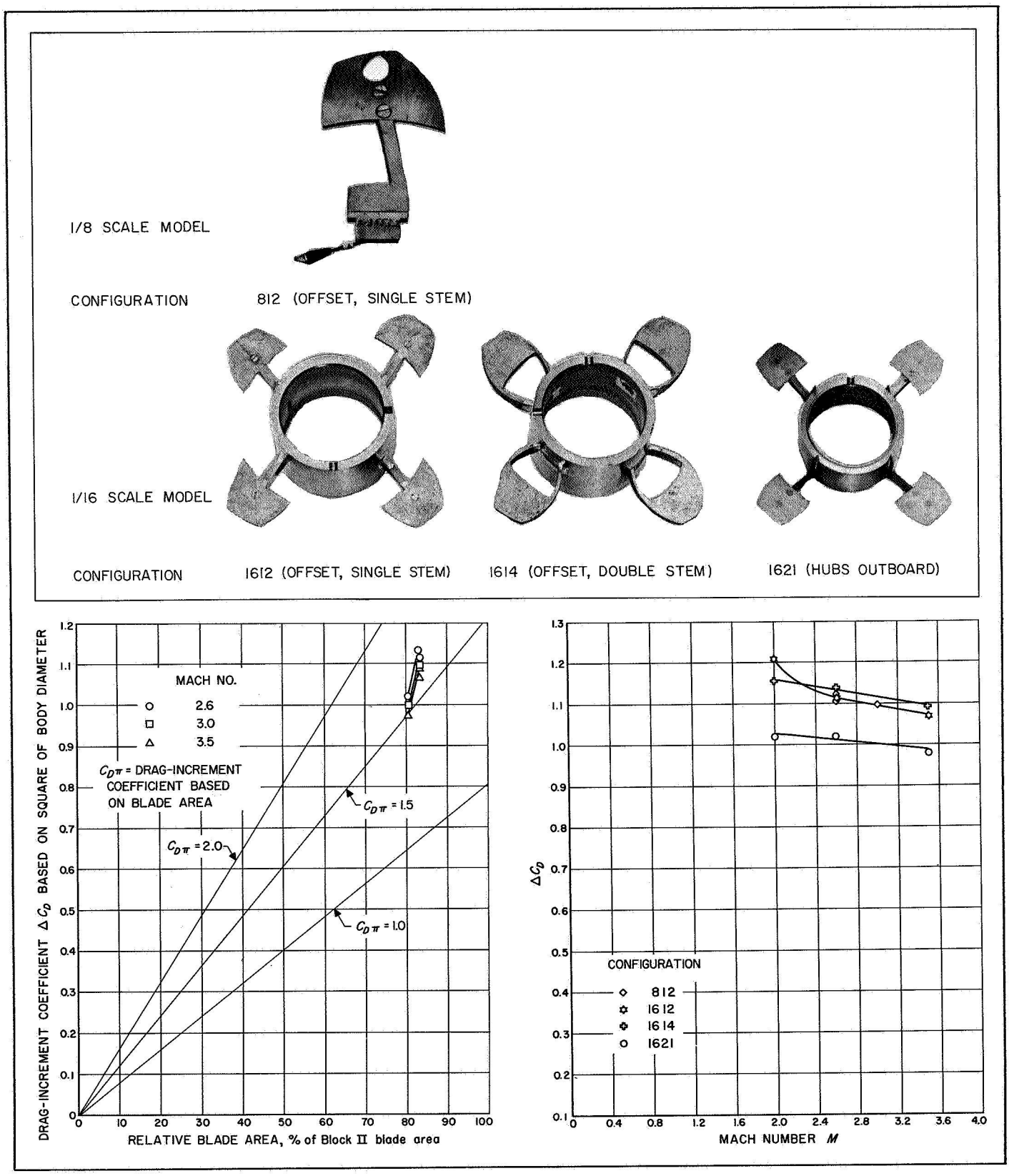


Fig. 34. Blade Configurations and Drag-Increment Characteristics of Oversize Planform Family, SWT 20-295

The oversize planforms (Fig. 34) were tested to determine whether major redesign of the brake compartment should be considered.

Figure 35 shows the air-flow patterns associated with various configurations at Mach numbers of 2.0 and 3.5, respectively. From these shadowgraphs it may be

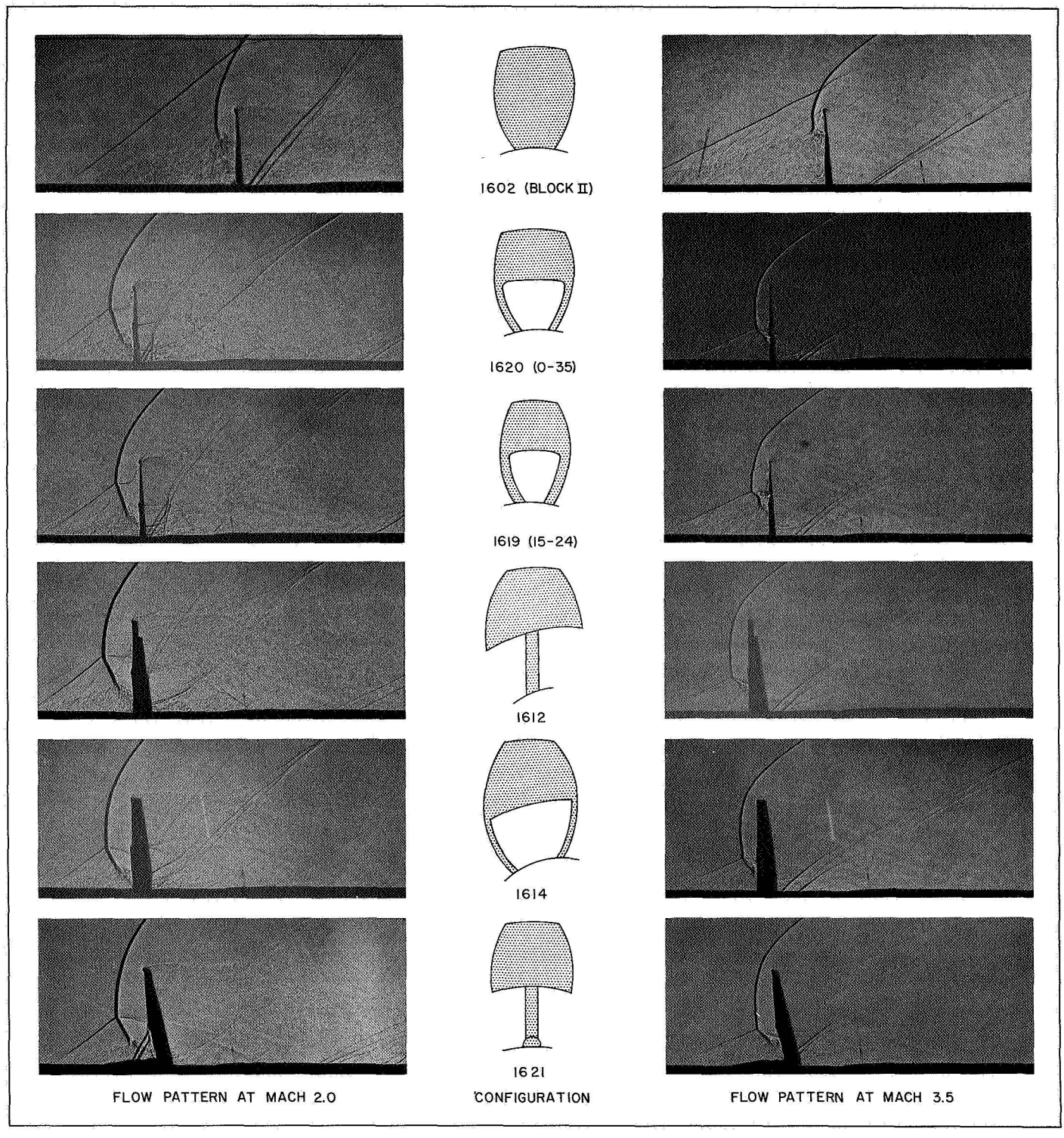


Fig. 35. Flow Patterns Produced by Various Planforms with Model at Zero Angle of Attack, SWT 20-295

seen that on the solid, Block II blade the separated-flow region tends to expand as Mach number increases, thus blanketing an increasingly large portion of the blade area. This phenomenon would seem to explain why the drag of such a blade decreases with Mach number. Shadowgraphs of the flow over the modified blades indicate that the effect of the root cutout is to reduce the size of the separated-flow region and to restrict its growth with Mach number. The reduction in the separation forward of the blade, in turn, causes the intersection of the oblique and normal shocks to move inboard. The slipsteam issuing from the shock intersection will flow over the blade tip in certain cases, and through the cutout in other cases.

Analysis of the shadowgraphs for all configurations revealed that within a given family of planforms there was close correlation between separation length and drag-increment coefficient. These correlations are presented in Fig. 36. Since the separation length may be considered as one indicator of vibration-producing potential, Fig. 36 provides a basis for comparing the potential of the three planform families at any specified drag-increment coefficient.

In test SWT 20-295 an attempt was made to measure sound-pressure level by means of barium-titanate crystals instead of the condenser microphones used previously. In Fig. 37 the root-mean-square output of one of the crystals on the body surface is presented in terms of a dimensionless parameter which normalizes the measurement on the basis of the drag increment. There is evidence that a large portion of the observed excitation of the crystal may have been due to accelerations associated with vibration of the model, and therefore no significance can be attached to the absolute levels of the signals observed. From the results shown in Fig. 37, however, it may be concluded that the Block II drag-brake blade (Configuration 802) produced considerably more aerodynamic noise per unit drag than did any of the other dragbrake configurations tested. Unfortunately, the uncertainty in these crystal measurements precludes further comparative evaluation of the various configurations.

Static-stability data obtained in test SWT 20-295 indicates that the nonsymmetrical, oversize blades (configurations 1612 and 1614) had a destabilizing effect which shifted the missile center of pressure forward by as much as 1 caliber from its brake-retracted location, while the center-of-pressure shifts associated with the other configurations were within acceptable limits (0 to 1 caliber increase in stability margin).

Undesirably large rolling moments at small angles of attack were observed with nonsymmetrical blades; the other configurations gave no appreciable moment effects.

C. Revised Trajectories

The procedure for generating trajectories such as those used for the Block I flight tests was based on guidance considerations only, with no restriction on the maximum drag force. On such trajectories the first brake opening

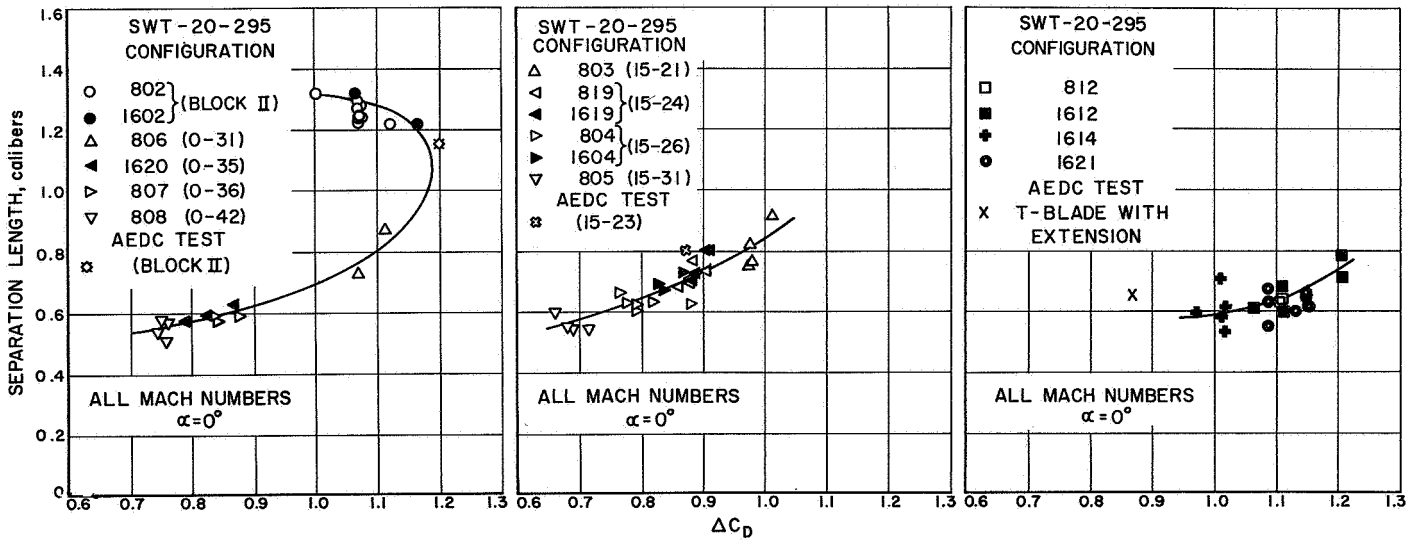


Fig. 36. Correlation of Separation Length with Drag-Increment Coefficient, SWT 20-295

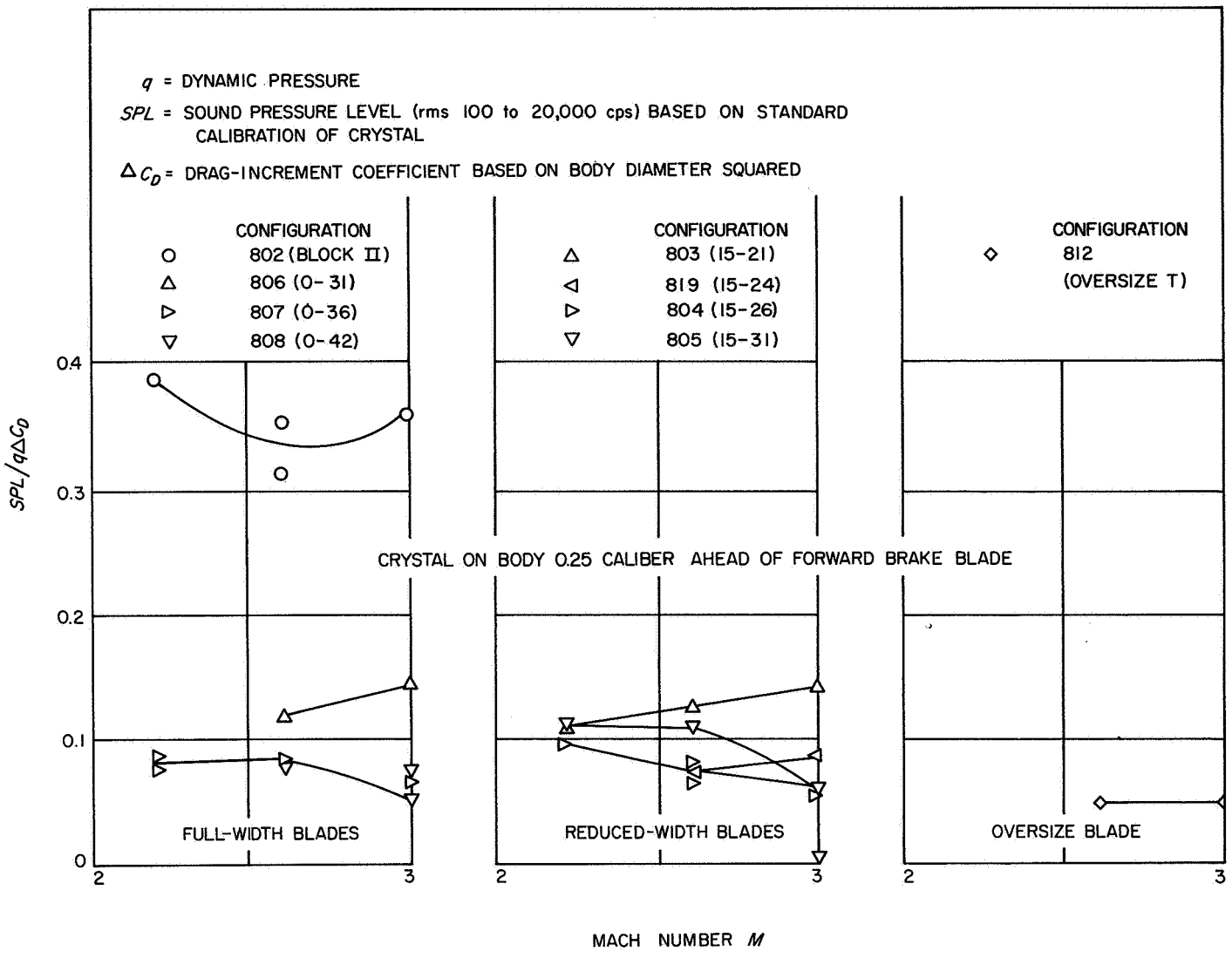


Fig. 37. Aerodynamic Noise Normalized on Drag Increment, SWT 20-295

was scheduled near the end of motor burning; since the braking occurred at very high values of dynamic pressure q, correspondingly high drag loads were encountered during braking.

As part of the program for developing methods of reducing the vibration environment, a study was made of various possible schemes for effecting range control without excessive drag force. The scheme which was selected, and which was introduced into the flight test program beginning with Flight 13, is one in which the values of q (and also M) during braking are minimized by scheduling the initial dragbrake period to begin as soon as the missile reaches a speed corresponding to a Mach number of about 1.1.

Under this scheme the first braking period is terminated at a preset time before motor burnout. In the revised procedure for generating trajectories, therefore, the first brake-closing time is varied together with the initial pitch angle[5] to obtain an acceptable summit altitude with a desired range. The second and third drag-brake-opening times are selected to provide sufficient flexibility to allow correction for underperformance as well as overperformance. The closing times for the second and third braking periods are determined in flight by the range computer, as before.

[5]Elevation angle at the end of the pitch maneuver which is performed during the first 11 sec after launch.

From a survey of revised standard trajectories it has been determined that the highest drag required for such trajectories is about 27,000 lb[6] as compared to over 50,000 lb for the former standard trajectories. In addition to reducing the maximum vibration input, this reduction in design load also provides an important improvement in the reliability of the dragbrake actuator and structural parts.

It should be noted that the reduction of the drag *level* during braking requires an increase in *duration* of braking in order to dissipate a given amount of total impulse. Thus, while the revised type of trajectory produces lower levels of vibration the vibration may exist for longer periods.

[6]In the revised standard trajectories the maximum drag and vibration are encountered on a minimum-range trajectory from a sea level launching with maximum propellant temperature.

IV. FLIGHT-TEST RESULTS

Phase II (Firings 9 to 18) of the *Sergeant* firing program included tests of the Block II blade planform and three different modifications, as shown in Fig. 7.

A. Tests of Block II Blade Planform

The vibration produced by the Block II dragbrake blades was measured on Firings 9, 11 and 13. Measurements in the axial direction at the aft-longeron location in these flight tests and in the AEDC wind-tunnel test (Section III-B-3) are compiled in Fig. 38, together with data from earlier flight tests in which the Block I blades were used. Although the earlier data were correlated with gross drag (see Fig. 8), it was found that a Mach number effect was also evident, and that an improved correlation could be obtained by using the product $(qd^2)M$.[7] As shown in Fig. 38 the correlation holds approximately for both the Block I and the Block II blades.

The data presented in Fig. 38 indicate that, with the Block II blade planform, the expected vibration level (over the 20-to-2000-cps band) would be about 60 *g* rms at the maximum $(qd^2)M$ during braking on the old-style standard trajectories and about 34 *g* rms at the maximum

[7]For convenience the quantity qd^2 is used instead of q, even though d is constant.

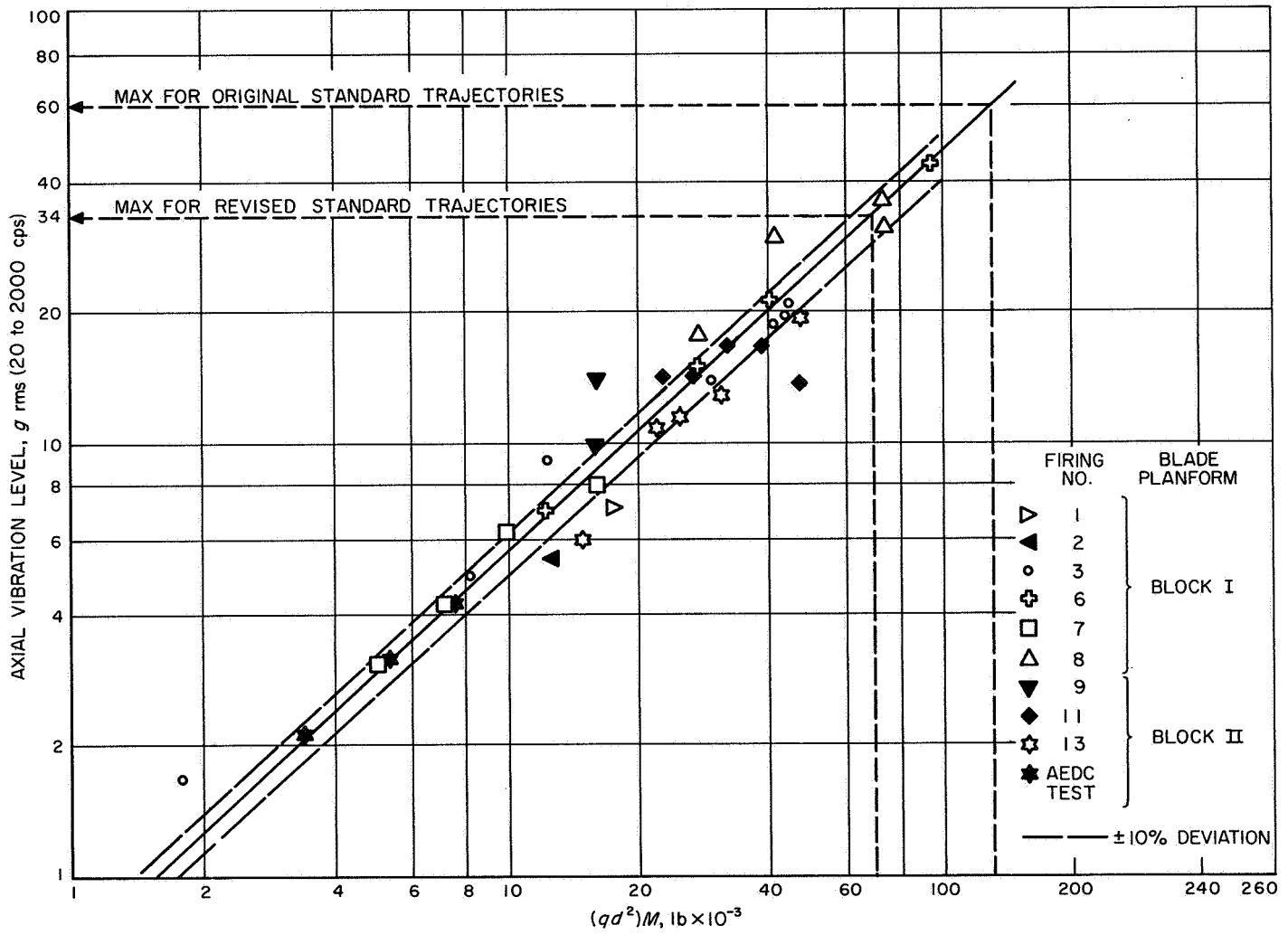


Fig. 38. Correlation of Aft-Longeron Vibration Measurements Obtained Using Block I and Block II Blades Extended

$(qd^2)M$ during braking on the revised standard trajectories described in Section III-C. Even 34 g, however, constitutes an undesirably severe handicap to the design of reliable guidance equipment.

In Figs. 39 and 40 the vibration levels measured in Firings 11 and 13 respectively are compared with levels predicted using postflight trajectory data together with the relationship presented in Fig. 38. Firing 11 was a long-range flight using an old-style trajectory. Firing 13 was a short-range flight using a revised trajectory.

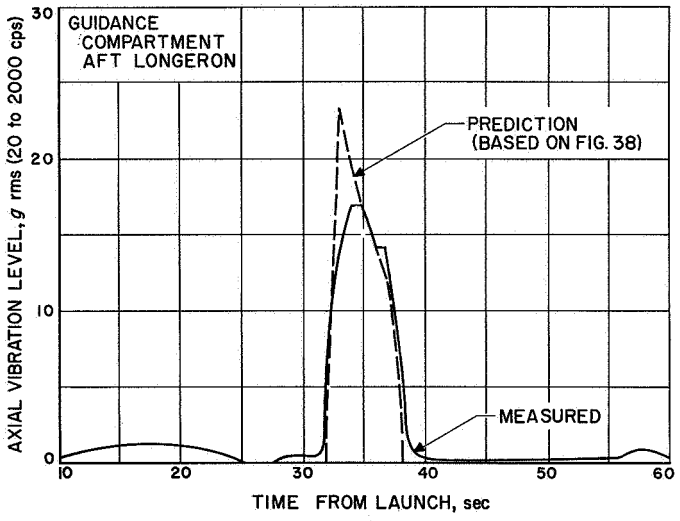


Fig. 39. Vibration Produced by Block II Blades, Firing 11 (Long Range)

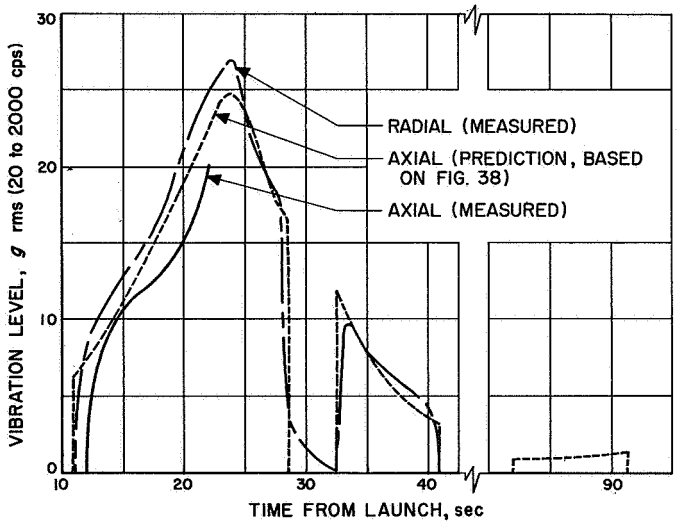


Fig. 40. Vibration Produced by Block II Blades, Firing 13 (Short Range)

B. Tests of Modified Blade Planforms

The first of the modified blade planforms (Fig. 7b) was flight-tested on Firings 14, 15 and 16. The modification involved a reduction of blade width corresponding to a reduction of 15% of the Block II blade area and a cutout at the blade root corresponding to a reduction of 23% of the Block II area. This blade was designed for the maximum drag load occurring in old-style standard trajectories; consequently, the struts (at either side of the cutout) were larger than necessary for loads occurring in the revised standard trajectories.

When the modified blades were in the fully-extended position on Firings 14, 15, and 16, the vibration levels observed were less than one-half the levels which the Block II blades would have produced. In Fig. 41 the accelerometer record obtained on Firing 14 (short range) at the aft-longeron location is compared with the vibration level which would have existed on the same trajectory if the Block II blade planform had been used. The Block II estimate here was obtained from Fig. 38 using $(qd^2)M$ values from postflight trajectory calculations. Vibration reductions similar to that shown in Fig. 41 were also achieved in Firing 15 (short range) and Firing 16 (long range).

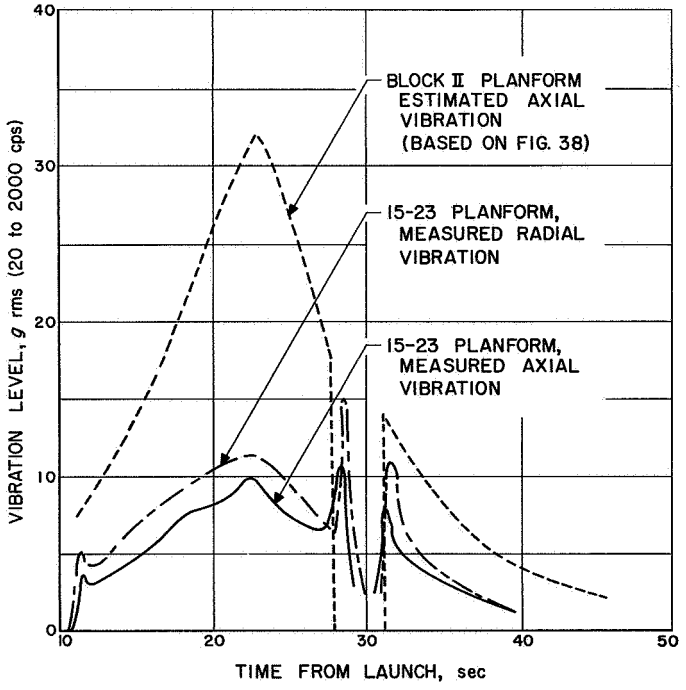


Fig. 41. Vibration Produced by Modified Blades, Firing 14 (Short Range)

The sharp peaks in the vibration level observed during the opening and closing operations of the modified blades (see Fig. 41) give evidence that the proximity of the braking area to the missile body is an important factor in the production of aerodynamic noise.

By means of a "brute force" post-flight trajectory simulation technique[8] it has been estimated that on Firings 14, 15 and 16 the average drag-increment coefficient ΔC_D was approximately 0.8, at Mach numbers of 2.5 and 3.5.

In Firings 17 and 18 an experiment was performed to compare the relative merits of a full-width planform (Fig. 7c) and a reduced-width planform (Fig. 7d) both having cutouts at the blade root. Both flights were medium-range flights. Thus, a direct comparison of the two types of blade planform was obtained under conditions capable of producing a relatively high vibration environment.

These blades were designed for the reduced loads corresponding to the revised standard trajectories. The reduced loads allowed the struts to be made narrower with a correspondingly wider cutout at the base of the blade.

For desirable guidance characteristics an average ΔC_D of 0.9 was considered to be the minimum acceptable. Blade dimensions which, according to results of SWT 20-295 and 20-324, would give about 10% more drag than the blades used in Firings 14, 15 and 16 were, therefore, chosen for Firings 17 and 18.

For the full-width blade tested on Firing 17 (Fig. 42) the area removed by the cutout amounted to 33% of

[8]This is a machine-computation procedure in which the guidance system is functionally simulated and successive trial values of ΔC_D are inserted until the second braking period is suitably reproduced.

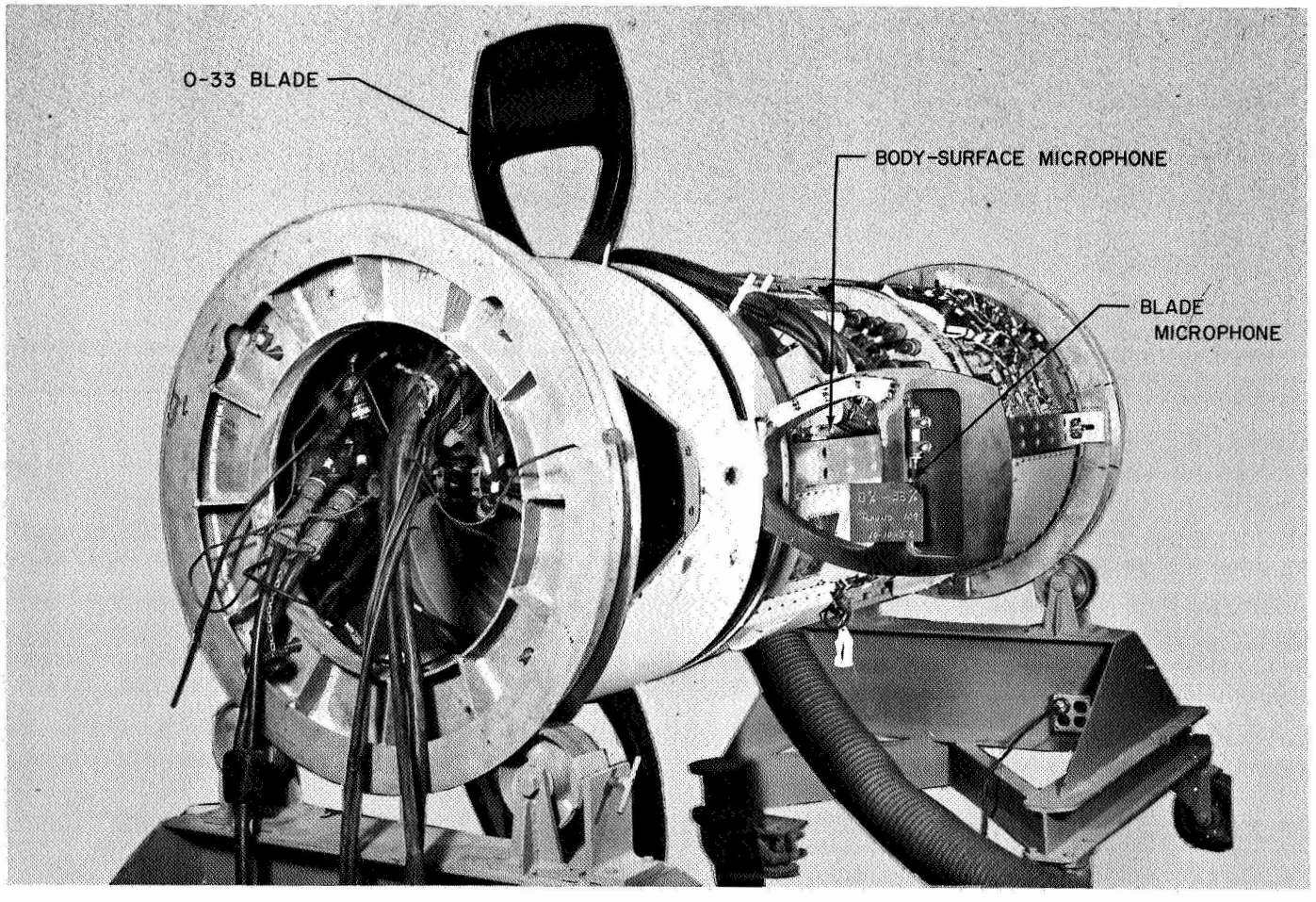


Fig. 42. Rear View of 0-33 Dragbrake Used on Firing 17

the Block II blade area. For the reduced-width blade tested on Firing 18 (Fig. 43) 14% of the Block II area was removed from the sides and 23% by means of the cutout. By virtue of the narrower struts, the radial dimension for a 23% cutout was smaller on this blade than on that used in Firings 14, 15 and 16; consequently, more of the braking surface lay in the high-drag region outboard of the cutout.

Sound-pressure measurements obtained from the Altec Lansing microphones indicated on Figs. 42 and 43 are presented in Fig. 44. However, comparable data for the Block II type of blades are not available.

Figure 45 shows the accelerometer records obtained at the aft-longeron location on Firings 17 and 18. These are compared with the corresponding estimated vibration level for the Block II blades on a similar trajectory. The results indicate no significant difference between the vibration environment produced by the 0-33 blades and that produced by the 14-23 blades. Furthermore, this vibration environment was just as low as was produced by the type of blades used on Firings 14, 15 and 16, even though the drag-increments obtained on Firings 17 and 18 were appreciably higher than in the previous three flights.

In Fig. 46 the relationship between the standard-location vibration level and $(qd^2)M$ is shown for all of the modified-blade flight tests. For reference the corresponding correlation obtained with the Block II blades (Fig. 38) is also shown. Data obtained with the 15-23 blade in the AEDC wind-tunnel test (Section III-B-3) are also included in Fig. 46. It should be noted that the vibration levels observed at the high values of $(qd^2)M$ in flight were considerably lower than would be predicted by extrapolation from the three data points obtained in the wind tunnel test.

The spread in the flight-test data presented in Fig. 46 indicates that the vibration produced by the modified

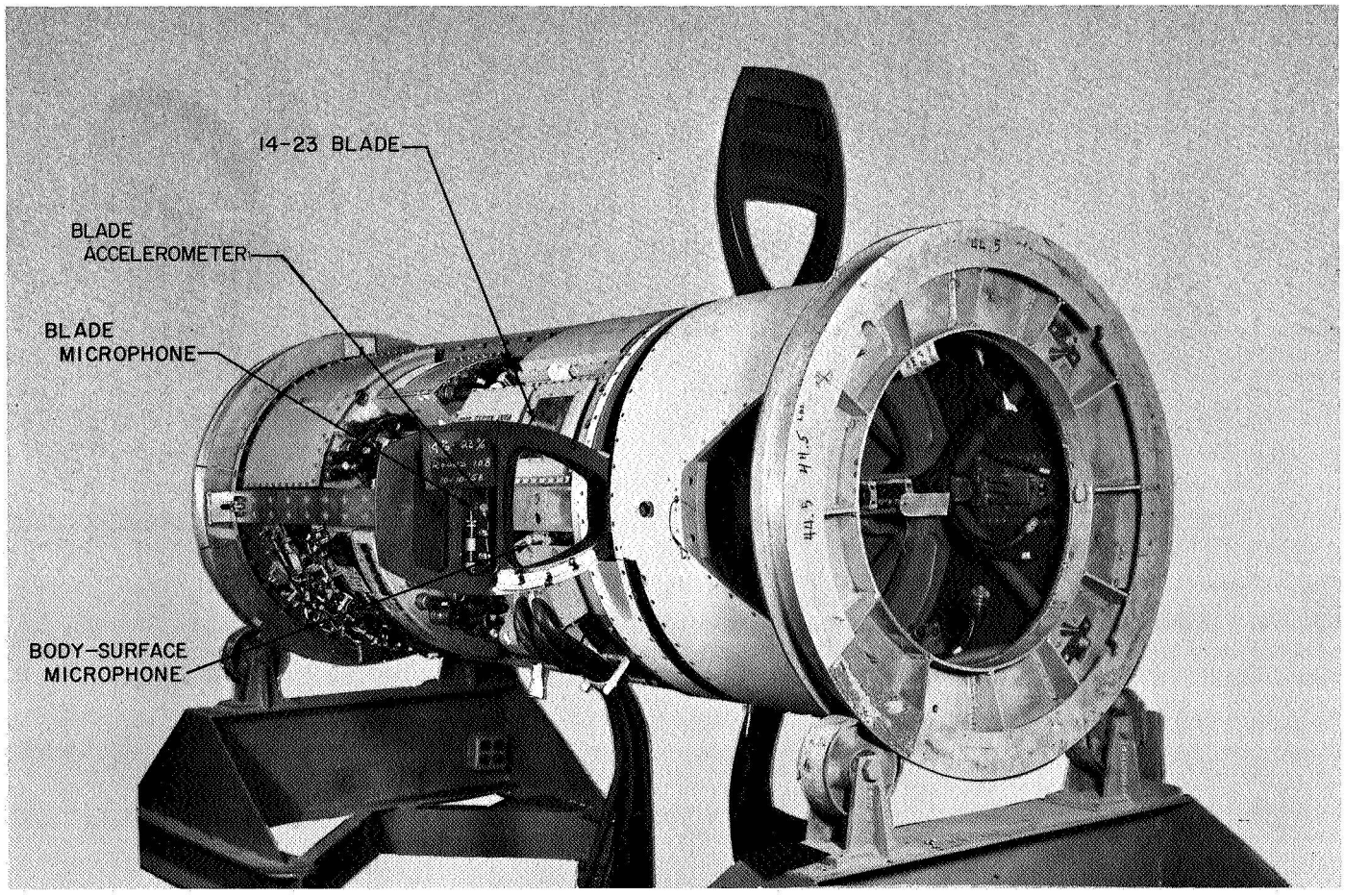


Fig. 43. Rear View of 14-23 Dragbrake Used on Firing 18

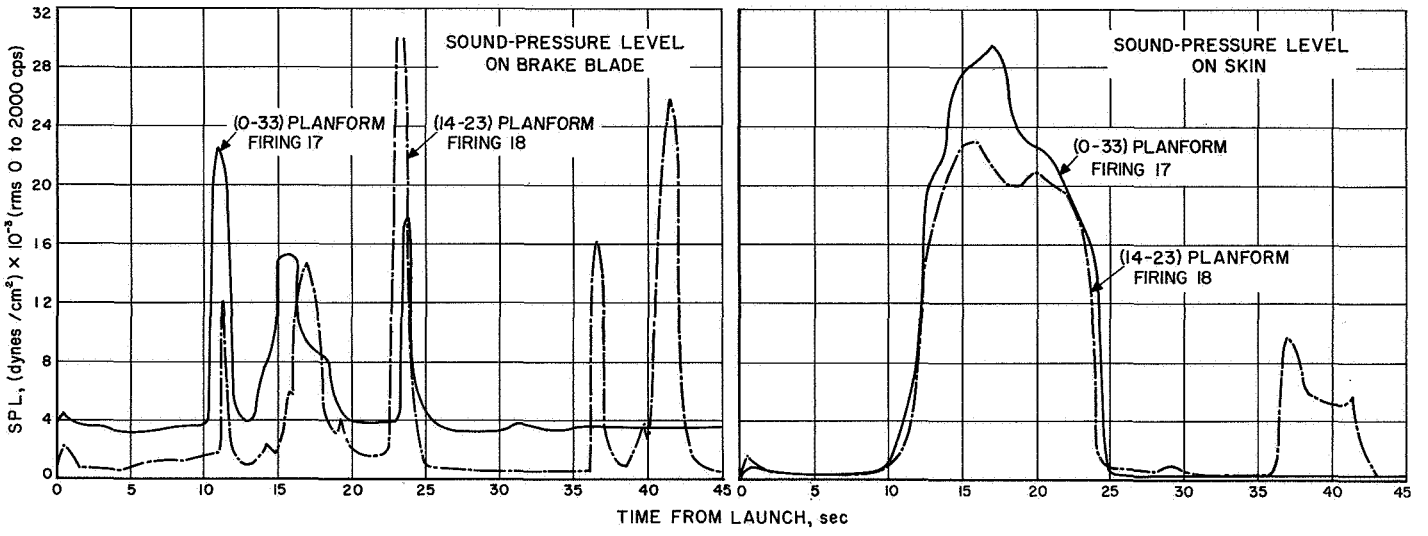


Fig. 44. Aerodynamic Noise Produced by Modified Blades on Firings 17 and 18

blades is not entirely dependent on $(qd^2)M$. The flight conditions covered, however, are sufficiently representative to conclude that, under the worst conditions to be encountered with the revised standard trajectories, the modified blade planforms will produce a vibration input of about 12 g rms (20-to-2000-cps band), except, of course, for the peak levels that occur for a very short time during extension or retraction of the blades (see Fig. 45).

The estimated values of the drag-increment coefficient ΔC_D obtained with the various types of dragbrake blades tested in Phase II of the *Sergeant* flight test program are summarized in Fig. 47. Over a Mach-number range from 1.1 to 2.4, the 0-33 blades tested on Firing 17 gave an average ΔC_D of 1.0, while the 14-23 blades tested on Firing 18 gave an average ΔC_D of 0.9. These estimates were obtained by the "brute force" simulation technique.

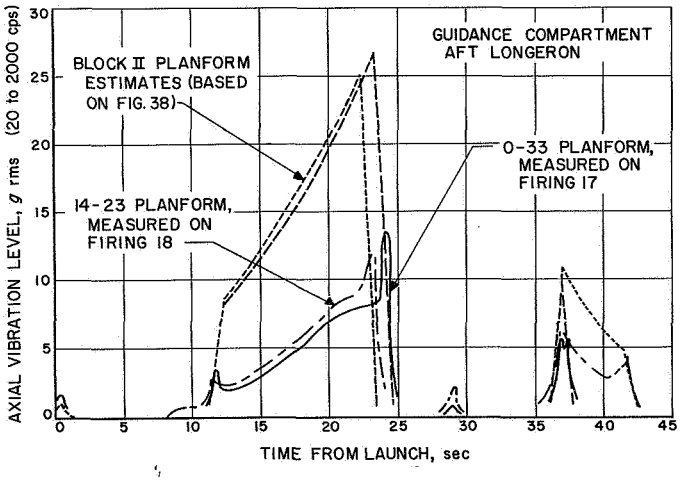


Fig. 45. Vibration Produced by Modified Blades on Firings 17 and 18

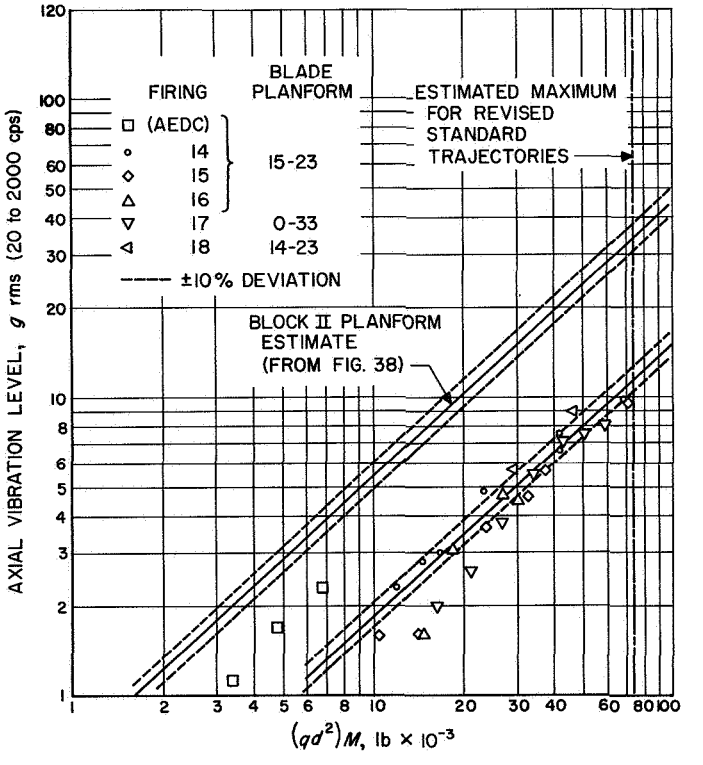


Fig. 46. Correlation of Aft-Longeron Vibration Measurements Obtained Using Modified Dragbrake Blades Extended

Although the absolute values are quite approximate,[9] the difference between the two values is considered relatively accurate.

The greater correction capability afforded by the 0-33 blades will permit the use of higher summit altitudes at long range, thereby increasing the maximum attainable range. For this reason, the 0-33 planform has been selected for use on the remaining experimental-model rounds which constitute Phase III of the firing program. If in that phase of the program this blade is proven to be satisfactory, it will also be utilized in the final design of the dragbrake for the engineering model and the tactical model.

[9]Estimated accuracy is ±5%.

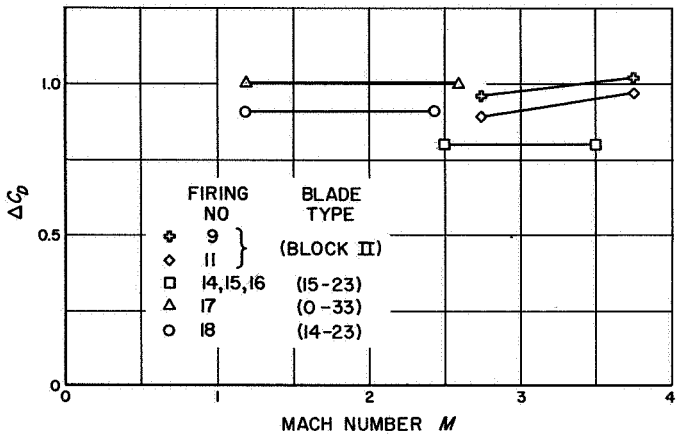


Fig. 47. Drag-Increment Coefficients Obtained in Flight

V. CONCLUSIONS

By devising a flight-trajectory scheme in which the primary dragbrake operation occurs at low supersonic Mach number and reduced dynamic pressure, the maximum required drag load, formerly 50,000 lb, was reduced to 27,000 lb; the maximum vibration input expected with the Block II dragbrake-blade planform was reduced from a level of 60 *g* rms to a level of 34 *g* rms in the 20-to-2000-cps band.

Aerodynamic modifications of the dragbrake-blade planform further reduced the maximum expected vibration input (in the 20-to-2000-cps band) from a level of 34 *g* rms to a level of 12 *g* rms or less without sacrificing drag. The latter level represents a vibration environment in which satisfactory performance of guidance equipment can be realistically expected.

The 0-33 blade planform tested on Firing 17 and the 14-23 blade planform tested on Firing 18 provided equal reductions in the vibration environment, and both provided adequate drag increments for the range-correction capability needed to satisfy the *Sergeant* official Military Characteristics. The 0-33 blades, however, produced about 10% more drag than the 14-23 blades. With the higher-drag planform the operating range of the *Sergeant* missile can be extended significantly. Consequently, the 0-33 blade has been tentatively selected as the configuration to be incorporated into the final dragbrake design.

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